MODELING STUDIES ON THE RESPONSE OF WEAPON FOUNDATIONS IN SOILS

by

Peter S. Westine

PHASE II FINAL REPORT

Contract No. DA-23-072-AMC-282(W)
SwRI Project No. 02-1548

Prepared for

U. S. Army Weapons Command
Rock Island Arsenal
Rock Island, Illinois

March 10, 1966

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ABSTRACT

In this report, the author first describes the design of a portable model foundation loading device capable of applying square wave impulses with forces up to 1200 lbs. for durations between 10 and 120 milliseconds. The model loading device is used to simulate the load on the non-recoiling parts of a howitzer foundation in both sands and clays. An important part of this program is the comparison between residual displacements and rotations resulting from loading a geometrically similar 1/5 scale, replica model and firing a 105 m. m., M2A2 howitzer. Through this program, considerable insight has been obtained into the dynamic response of artillery foundations. The foundation response lies in neither a quasi-static analysis nor an impulse analysis realm. Load level, the duration of loading, soil strength, the mass of the foundation, and the mass moment of inertia of the foundation are all significant in determining the response of artillery foundations. Furthermore, the vertical translational, horizontal translational, and rotational responses of the foundation should be coupled in any dynamic analysis of the response. This report includes plans for an experimental program to develop data for analyzing the response of artillery foundations and closes with a discussion of some experimental results in clay soil.

ACKNOWLEDGEMENTS

In a program as complex as this, the principal investigator relies heavily on assistance from many individuals. He gratefully acknowledges the guidance provided by the Army's technical representatives at Rock Island Arsenal, Miss Catherine Fitzpatrick and Mr. Oscar Wilhelm. Mr. Edwin Espey, owner of the A-1 Silica Sand Company, generously permitted the author to conduct the model-prototype comparison described in Section IV on his land. Personnel in the 4th Army, Mr. Briggs, Mr. Staudt, Mr. Fifer, Mr. Bellitzer, Colonel Allen, and Colonel Kenagy, were all helpful in obtaining ammunition and assistance for the model-prototype comparison. The author especially appreciates the support that was provided by Colonel John Kenagy, Captain Duane Spiess, Lieutenant Stigent, and their men of the 40th Artillery Battalion, 8th Corp, 4th Army. These men spent three weekends in the field with SwRI personnel firing artillery for the model-prototype comparison. A complete list of SwRI personnel who contributed in some measure is impossible; however, the author thanks Dr. G. E. Nevill, Jr., for initial program planning; Mr. Luis Garza and Mr. E. J. Baker, Jr., for the design and calibration of the model loading device; Mr. Donald Saathoff for data reduction; Mr. Victor Hernandez for drafting the drawings in this report; Mr. Curtis Walker for the photography; and Mr. Robert Stiles and Mr. Richard Roemer for calibration of the model loading device. Special appreciation is due Mr. James Sharp who constructed the models and performed the field work for this program.

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I. INTRODUCTION

The designer faced with planning future artillery has many competing factors to consider. These factors include needs for simplicity, reliability, ruggedness, accuracy, fire power, minimum cost, minimum time for emplacement, and maximum mobility. Generally speaking, one cannot achieve all of these desirable qualities since many are mutually exclusive. Hence, any practical weapon will be a compromise among numerous competing requirements.

Presently, the art of gun design permits the mechanical portions of the weapon to be designed with a high degree of refinement; however, that portion of the problem involving soil response is not well defined, as present knowledge is inadequate to allow reliable predictions of displacements when foundations are subjected to impulsive loads. This limitation represents a serious restriction in the design of future weapon footings and mounts, particularly from the viewpoint of firing stability.

The general weapon foundation problem is a coupled structural and soil dynamics problem in which the soil is subjected to repeated impulsive loads. One would like to anchor artillery pieces and prevent residual rotation of the foundation from occurring with each repeated impulse. An artillery piece that does not rotate would increase weapon accuracy and fire power. The permanent displacements that result from the firing of artillery do not influence weapon accuracy and fire power to

the same degree that permanent rotations influence weapon stability. The displacements resulting from the firing of 40 to 60 rounds of a gun with a 2 mile range would finally cause the same loss in accuracy as a 1 mil residual rotation. The weapons designer should create a weapon that might displace, but should not rotate with each shot. To achieve this aim, the designer must be able to analyze the dynamic response and interaction between the weapon foundation and the soil.

The most difficult portion and unfortunately the crux of the mechanics in this problem, is the development of the soil-structure interaction which determines the external forces applied to the stakes and spades, the anchoring elements of artillery foundations. As the foundation is loaded, a distributed soil reaction is developed against the surface of anchoring elements. If the distributed force were known over small time intervals, the resulting external forces applied to stakes and spades could be rigorously obtained in magnitude, direction, and point of application. With such knowledge, the determination of acceleration, velocity and displacement would be achieved. The solution of this significant phase in the problem is not a simple matter, but it represents the basis for our program.

This report covers the second phase of a three part research program to study the response of foundations and foundation components when subjected to dynamic loads. The emphasis is placed on developing a procedure for analyzing the dynamic response of soils and the resulting

interaction between artillery foundations and the soil. With such information, future weapons could be designed to provide improved firing stability.

The first phase together with its objectives and results is discussed in reference 1. A proposal has already been drafted and submitted enumerating the objectives for the third or final phase, reference 2. Our present phase, Phase II, had as its objectives:

1. The design and fabrication of a model loading device.
2. The checkout and verification of the device.
3. A model-prototype comparison for a quantitative evaluation of accuracy.
4. The planning of a test program to collect field data on the response of stakes and spades from transient loads.
5. The collection of a significant portion of that field data.

Objectives 1 and 2 on the design, development, and fabrication of a field model loading device are described in Section II of this report. Section II discusses the model loading device, describes its operation, and presents typical traces of the load history obtained by using the instrument. Section III of the report presents a short review of soil modeling together with a listing of the advantages and disadvantages inherent in the approach. This section places the interpretation of test data in its proper prospective. Section IV compares the residual motion resulting from the firing of 105 m.m. howitzer to the residual displace-

ments and rotations of a corresponding 1/5 scale model. The comparison between model and prototype results, objective 3, is made at both a sand and clay site. In the course of determining the dynamic response of howitzers, tests carried out to assess the importance of mass, load duration, and coupling of the modes of response are described in Section V. Section VI presents the field data collection program, objectives 4 and 5. Further comparisons between 1/5 scale and 1/3 scale model foundation anchoring elements are made in Section VII, and Section VIII concludes the report.

II. MODEL LOADING DEVICE

During the firing of a howitzer, weapon recoil mechanisms apply a force of essentially constant magnitude to the non-recoiling parts of the artillery foundation. For this reason, a model loading device was designed and fabricated to apply a scaled dynamic loading to foundation models.

To determine the required operational characteristics, we had to establish representative load levels and durations from actual weapon rod pull data. Evaluation of data for the 105 m.m. Howitzer XM102, 155 m.m. Howitzer M2, 75 m.m. Pack Howitzer M1A1, and XM70, indicated force levels varied widely (to maximums over 50,000 pounds) and load durations fell within a relatively narrow range from 50 to 600 milliseconds. Since the load would generally be distributed to two or more foundation elements, we decided to establish zero to 25,000 pounds and 50 to 600 milliseconds as prototype characteristic load ranges.

Next, one had to decide on an appropriate scale factor for model testing. A length ratio of 1/5 was selected as a compromise between excessive divergence from prototype size and the need for manageable load levels. For geometrically-scaled models tested in identical soils as for the prototype, this length ratio leads to a time scale ratio of 1/5 and a load scale ratio of 1/25 (see reference 1 for details). Thus, the model loading device must produce a square wave impulse with loads

from zero to 1000 pounds and with durations between 10 and 120 milliseconds. In addition to operating within these ranges, the device requires a sharp rise and decay time, must be operable in the field, portable, and capable of applying several thousand loadings without suffering irrepairable damage.

The resulting device can be seen in Figure 1 and is shown schematically in Figure 2. It operates as follows: With Mylar diaphragms in place, the main chamber is pressurized to a preselected level (up to 120 psi). Air gun pressure is applied and the trigger released. The air gun projectile breaks the small diaphragm to load the piston and ruptures the large diaphragm to unload the piston. The model loading device generates a square wave pulse with a force between 30 lbs and 1200 lbs and a duration that can be varied from 3 to 100 milliseconds. The magnitude of the load is determined solely by the pressure level in the main chamber. The projectile velocity determines the duration of the load which in turn is a function of the air gun pressure (up to 2000 psi from a nitrogen bottle), the thickness of Mylar diaphragms being ruptured, and the mass of the projectile.

To assure good square wave pulses, as can be seen in Figures 3, the main chamber must be pressurized to within 90 to 100 per cent of the pressure required to rupture the diaphragms. Different thicknesses of Mylar are used for different load levels in order to meet this requirement and obtain excellent square wave pulses. When the chamber

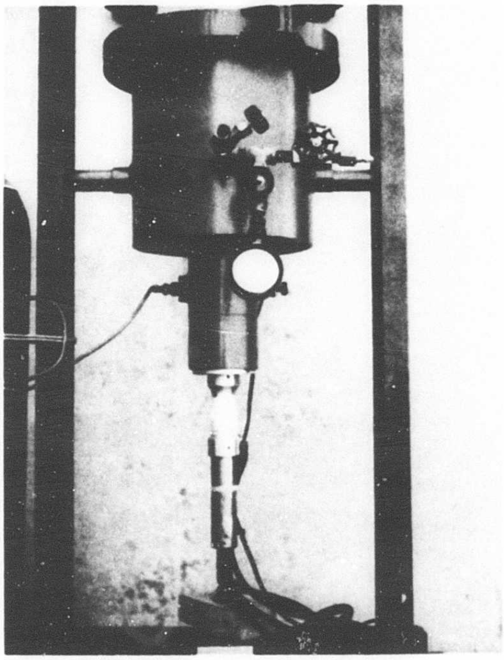


FIGURE 1. MODEL LOADING DEVICE

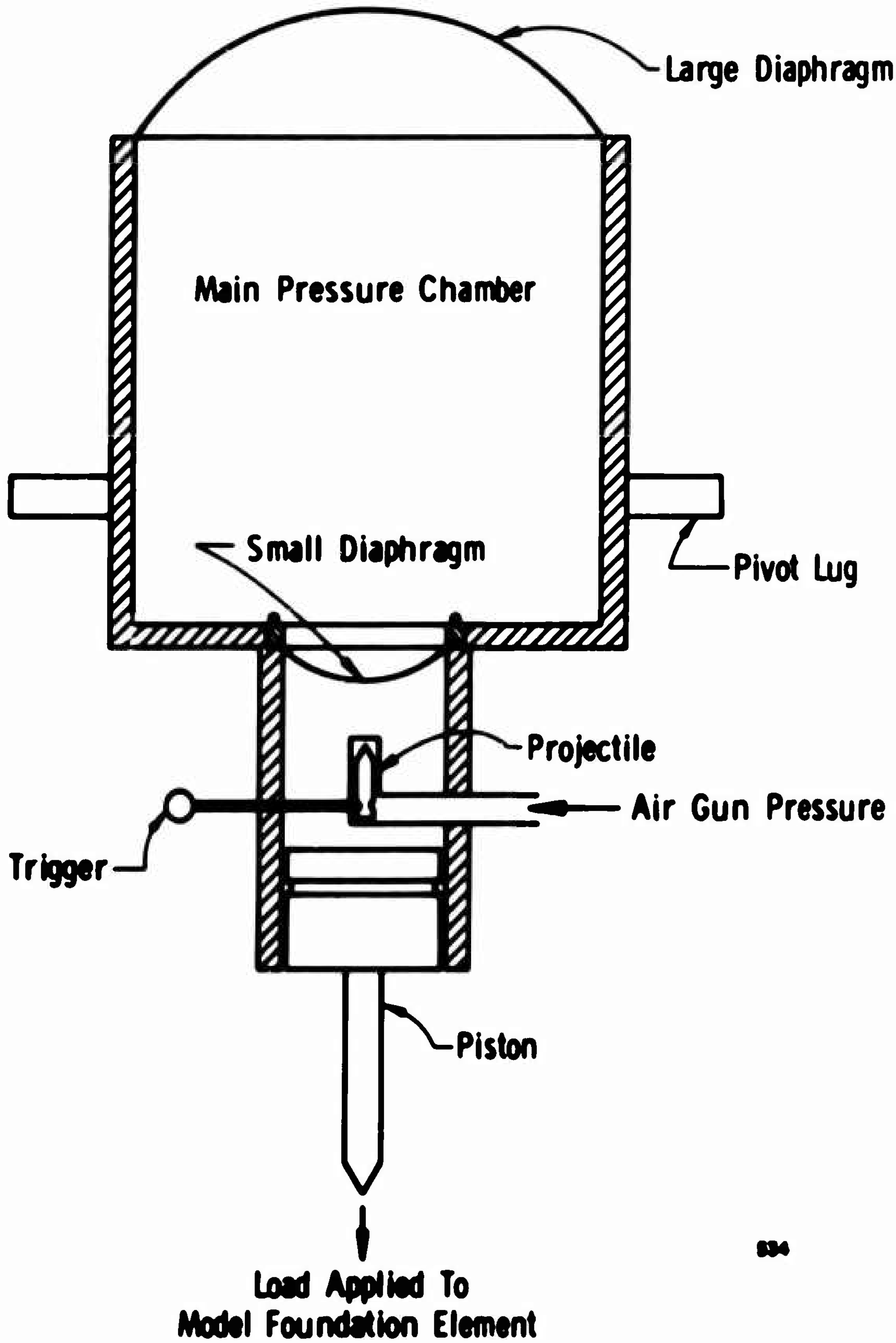
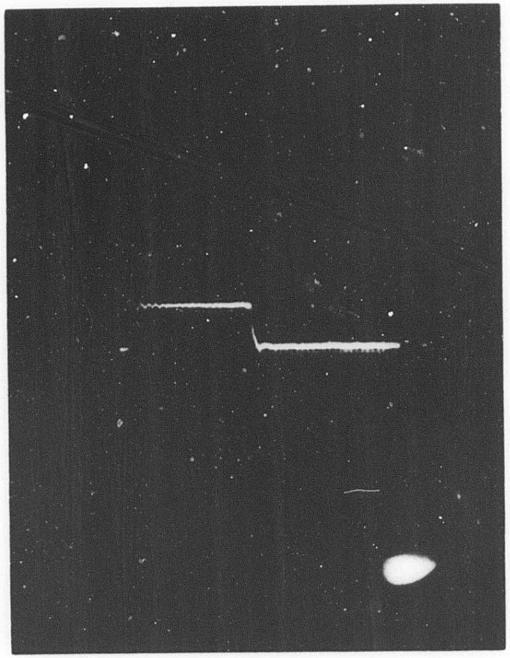
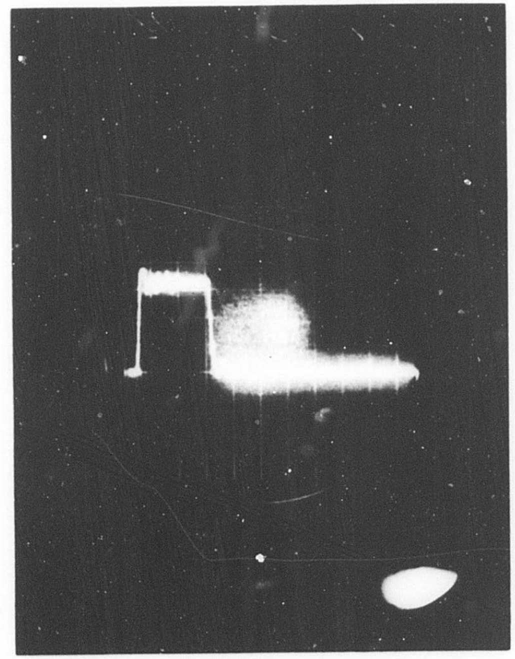


Figure 2. Schematic Drawing Of The Model Loading Device



FORCE LEVEL - 50 POUNDS
DURATION - 90 MILLISECONDS



FORCE LEVEL - 600 POUNDS
DURATION - 25 MILLISECONDS

FIGURE 3. FORCE-TIME HISTORIES OBTAINED WITH THE MODEL LOADING DEVICE

is pressurized to less than 90 per cent of the rupture level, the bullet punctures the Mylar, creating extended rise and decay times. With proper thickness of Mylar for specific pressure levels in the main chamber, the bullet rips the diaphragms and creates very sharp rise and decay times. The proper Mylar to be used for each force level was determined experimentally during calibration of the loading device.

To calibrate the model loading device, we mounted it in a rigid frame and placed a dynamometer section in the rod of the piston. The output from this dynamometer led to an amplifier and oscilloscope. Through the use of these instruments, we determined experimentally the duration of loading as a function of air gun pressure, Mylar thicknesses, and projectile mass. Graphs were made relating these variables for use in the field.

When mounted on the back of a 3/4-ton weapons carrier, this device is very adaptable to field work. Figure 4 is a schematic drawing of the model loading device cantilevered from the rear of the weapons carrier. Bottles of compressed air lying in the back of the weapons carrier pressurize both the main chamber and the air gun. The loading device can be translationally adjusted in all three orthogonal directions and can be rotated in the plane of the truck's chassis. The model loading device operating in this manner has been used to load model howitzers and model foundation anchoring elements. It will be used in Phase III to generate additional data on the transient deflections experienced by stakes and spades when these anchoring elements are dynamically loaded.

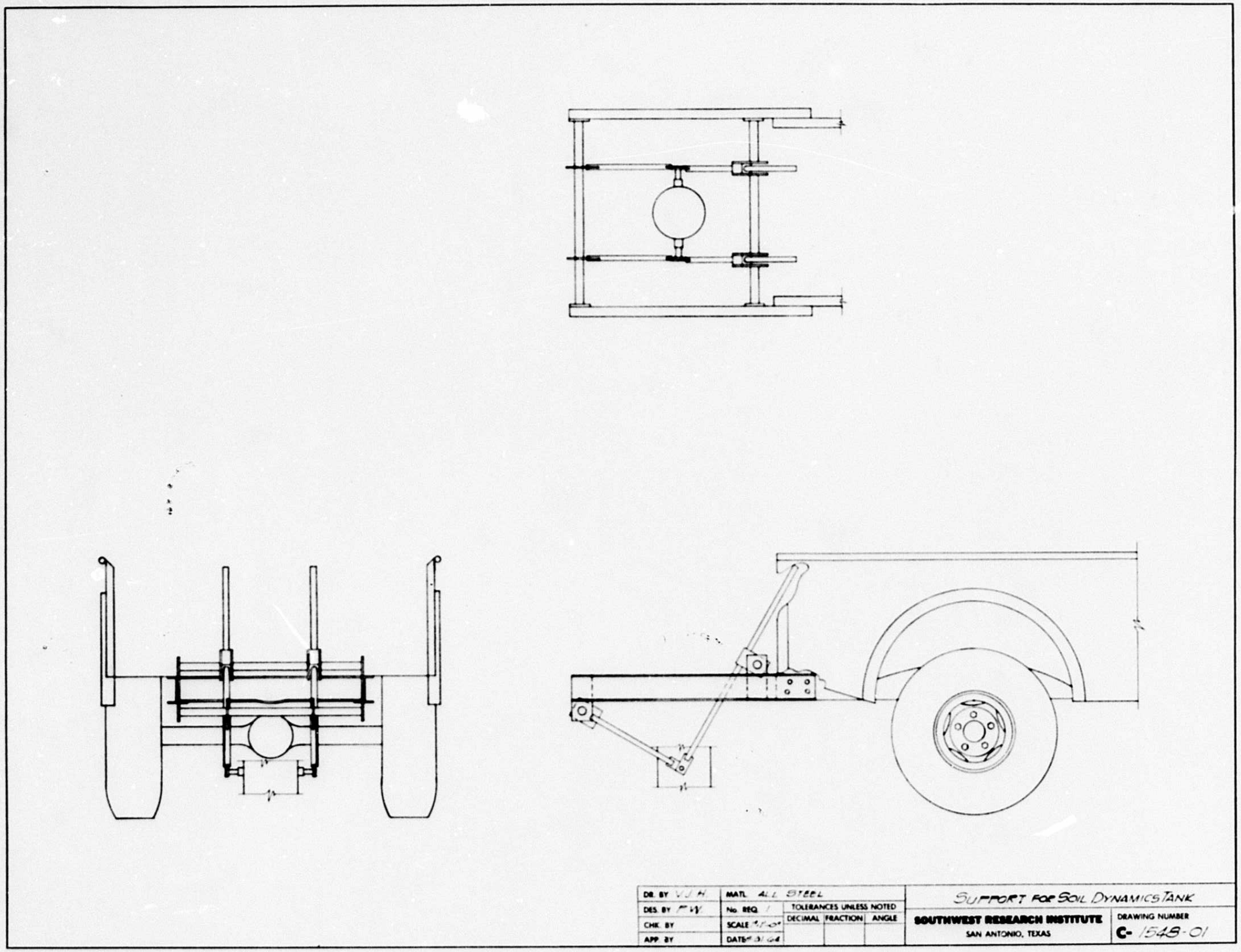


FIGURE 4. SUPPORT FOR SOIL LOADING DEVICE

III. MODELING OF SOIL-STRUCTURE INTERACTION

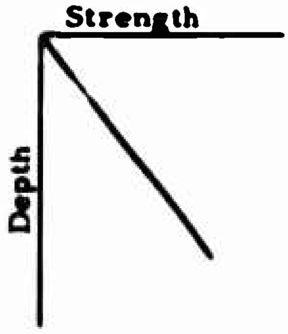
Before presenting results on model-prototype comparisons, stake and spade data, and experimental observations on foundation response, the author feels obliged to discuss soil dynamics modeling. Scaling philosophy fell under the objectives of Phase I; however, by noting the advantages and disadvantages of our approach, together with the restrictions on interpreting the data, the results and discussion attain their proper prospective.

The Phase I Final Report, reference 1, very adequately handles the formulation of our scaling. We are using replica scaling which calls for the same soil to be used in model and prototype tests. Model stresses, densities, strains, and velocities are identical to full scale values. Time scales as the length ratio, displacements scale as the length ratio, and force scales as the length ratio squared in our geometrically-scaled model. This approach simulates inertial effects and strength effects (the soil's stress-strain curve); however, it assumes gravitational effects and strain rate effects insignificant. Our scaling corresponds identically to other modeling of soils in the realms of stress wave propagation, transient loads on footings, and nuclear blast effects. Nevertheless, certain limitations and methods of interpreting the results arise which require elaboration.

The importance of strain rate in the scaling of soils depends upon the length ratio, as the strain rate is scaled proportionally to the

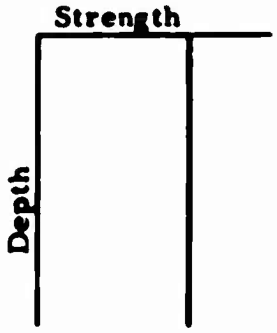
length ratio in replica models. Granular soils, in general sands, are very insensitive to strain rate. Tests at M.I.T. on both dry and wet sands[3] showed less than 10% change in a granular Ottawa Sand with an increase in strain rate from 10^{-1}%/sec to 10^{+3}%/sec. Unfortunately, cohesive soils can be strain rate sensitive; however, they need not be highly strain rate sensitive. Tests at the University of Washington[4], indicated that the degree of sensitivity depended upon the moisture content and the compaction, while tests at M.I.T.[5], indicated that their normally consolidated test soils were not sensitive for rates less than 0.1 %/sec, but were sensitive for rates greater than 0.1 %/sec. Further tests at Notre Dame[6], showed that normally consolidated clay exhibited little strain rate sensitivity, while over-consolidated clays exhibited strain rate sensitivity. Work at M.I.T. also found over-consolidated clays to be strain rate sensitive. In general, soils are not very strain rate sensitive for differences in load duration of less than an order of magnitude. This result was confirmed in our Phase I Final Report[1]. Strain rate sensitivity for 1/5 or 1/4 scale models plays an insignificant role in the model's response.

Gravitational effects play a more significant part in the response of models. This statement is particularly true with respect to granular soils. If one were to sketch the variation of strength with depth for a sand, strength would appear to increase hydrostatically with depth, as in Figure 5a. A model implanted in the same sand as the prototype



Granular Soil

FIGURE 5a



Cohesive Soil

FIGURE 5b

Variation of Soil Strength with Depth

structure would experience greater deflections than the prototype. To properly model this situation, one must scale "layering effects", (the soil's strength with depth). On the other hand, heavily over-consolidated clays experience insignificant gravitational effects. If one were to plot the variation of strength with depth in a highly over-consolidated clay, one finds no variation of strength with depth, as in Figure 5b. A word of caution is in order, as disturbed clays, remolded laboratory clays, and mildly over-consolidated clays exhibit a strength versus depth variation as in Figure 5a. Further discussion of this phenomenon may be found in reference 7. One readily observes that a poor model-prototype comparison results if the same soil used in both model and prototype experiments possesses a strength with depth variation as in Figure 5a. In Phase I, we demonstrated how an excellent correlation can result if the layering of a soil is modeled. When a model soil is created

by properly scaling the layering, model and prototype results for a 1/5 scale model can agree to within 5%. If a model soil is not created and the same soil is used for model and prototype tests, results can differ by as much as 50 to 100 per cent. This observation is very important, as it insinuates that we should not expect an excellent correlation between model and prototype howitzer results obtained in field tests. Prototype or full scale results, obtained from models tested without scaling the layering, actually apply to a prototype tested in the same soil with a different degree of compaction.

In the scaling of soil, one does not use a model medium with a scaled grain size. Such an approach is justified provided the dimensions of stakes, spades, or other foundation elements are very large compared to the mean diameter of soil grains. Although grain size is relatively unimportant in modeling soils, certain surface phenomena can play key roles. Clay soils crack or fissure when they are extremely dry. These fissures create lumps of clay approximately 1/2 to 2 inches in diameter. The displacements that would occur in a fissured soil are caused by the sliding of one clay lump over another. To model this behavior, one should scale down these lumps proportionally with the length ratio. Here in South Texas, a cohesive soil is especially susceptible to fissuring from desiccation. A badly fissured test medium would cause scaled-up model displacements to be significantly smaller than corresponding prototype results. Such a phenomenon is of major importance,

especially when the resulting lumps of soil are of the same size as the foundation anchoring elements.

To accurately scale a very rough terrain one must model the lumps, gutters, and ridges. Quite naturally, we are not taking such painstaking care in our data acquisition program. Roots, clumps of grass, and small voids beneath the surface can also cause problems in scaling.

Perhaps the most difficult problem in a soil simulation is the modeling of pore air and pore water pressures. A soil consists of a 2-phase medium, a granular solid phase and a liquid and/or gaseous fluid phase. In replica scaling, stresses, pressures and velocities are identical in model and prototype. This statement should be true regardless of the soil phase. In discussing the dissipation of pore pressures in the liquid and/or fluid phase, soil mechanicians use Darcy's Law or some other variation thereon. Darcey's Law claims that velocities are proportional to the rate of change of pore pressure with distance. The constant relating the spacial derivative of pressure to the velocity is a function of the soil. This constant (permeability) has the same value in a model and prototype test held in the same soil. One readily observes that this equation is not being satisfied using replica modeling, as the spacial derivative of pressure possesses dimensions of $\frac{\text{force}}{\text{length}^3}$, with pressures and velocities having a ratio of unity between model and prototype. This observation implies that

the dissipation of pore pressures is not properly scaled. The relative importance of this phenomenon on the scaling depends greatly on the density of the test media. To date, this phenomenon has no been properly pursued, and a discussion of the magnitude by which this behavior influences the results is impossible. Personally, the author feels that a model in a low density medium where the voids must be compressed during shearing, will have deflections that are too large. Similarly, a model in a high density medium where the voids must be expanded during shearing, will have deflections that are too small. The importance of these dilatational effects has been demonstrated in only a few experiments comparing the penetration of balls dropped into soils while under vacuum, to balls dropped into soils in the air[8,9]. Our Phase I drop tests into soils with simulated layering gave excellent results because the soil possessed either the correct density to exhibit no dilatational influences, or the added compaction of the model soil necessary to decrease the permeability sufficiently to scale the dissipation of pore pressures.

One should look upon a soil in which the layering and compaction has been simulated as a model medium different from the prototype medium. When the scaling of the layering and compaction is not performed, correlation between model and prototype results may be good or poor, dependent upon the influence of gravitational effects and soil dilitational behavior. The data generated using models in a test bed does not necessarily apply to larger scale elements in the same test bed; however, it would apply to larger scale elements in the same test bed under a higher degree of compaction. Thus, data obtained from experiments using model elements would apply to a scaled-up prototype soil.

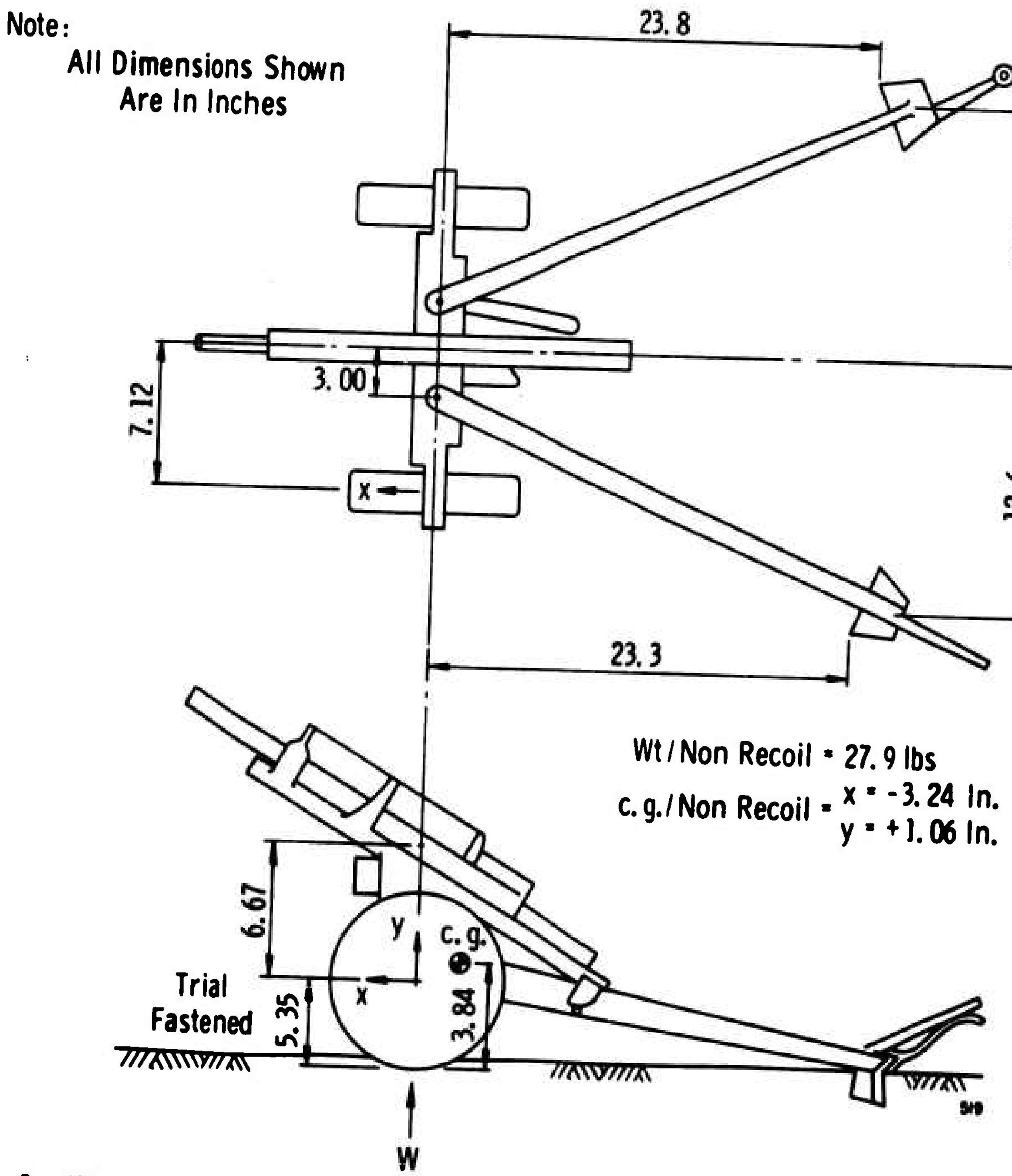
IV. MODEL-PROTOTYPE HOWITZER COMPARISON

We constructed a 1/5 scale, geometrically-similar, replica model of the non-recoiling parts in a 105 m.m. M2A2 howitzer. A square wave load time history could be applied to this model in a manner that simulated the draw bar pull experienced by a prototype howitzer. Figure 6 gives the dimensions and inertial properties of the model, and in Figure 7 the model may be seen. Prior to testing, the model was weighed, dangled, and swung to obtain experimentally the model's weight, center of gravity, and mass moment of inertia.

A model-prototype comparison has been conducted to obtain an additional quantitative evaluation of the accuracy to be expected from our program. Because sand and clay behave in such radically different manners, these tests were held at both a sand site in southern Bexar County and a clay site here on the Institute grounds. Each series of tests are discussed in turn.

Model-Prototype Comparison In Sand

The sand site employed in our model-prototype comparison consisted of a medium grained, poorly graded, dry, white silica sand of medium relative density from the Claiborne formation of southern Bexar County. Soil conditions are summarized in the appendix. Horizontal displacement, vertical displacement, and angular rotation were measured after each shot for a comparison between model and



I_{zz} / Non Recoil = 0.22 Slug-ft²

$I_{c.g.}$ / Non Recoil = 0.157 Slug-ft²

Figure 6. Model Dimensions And Properties

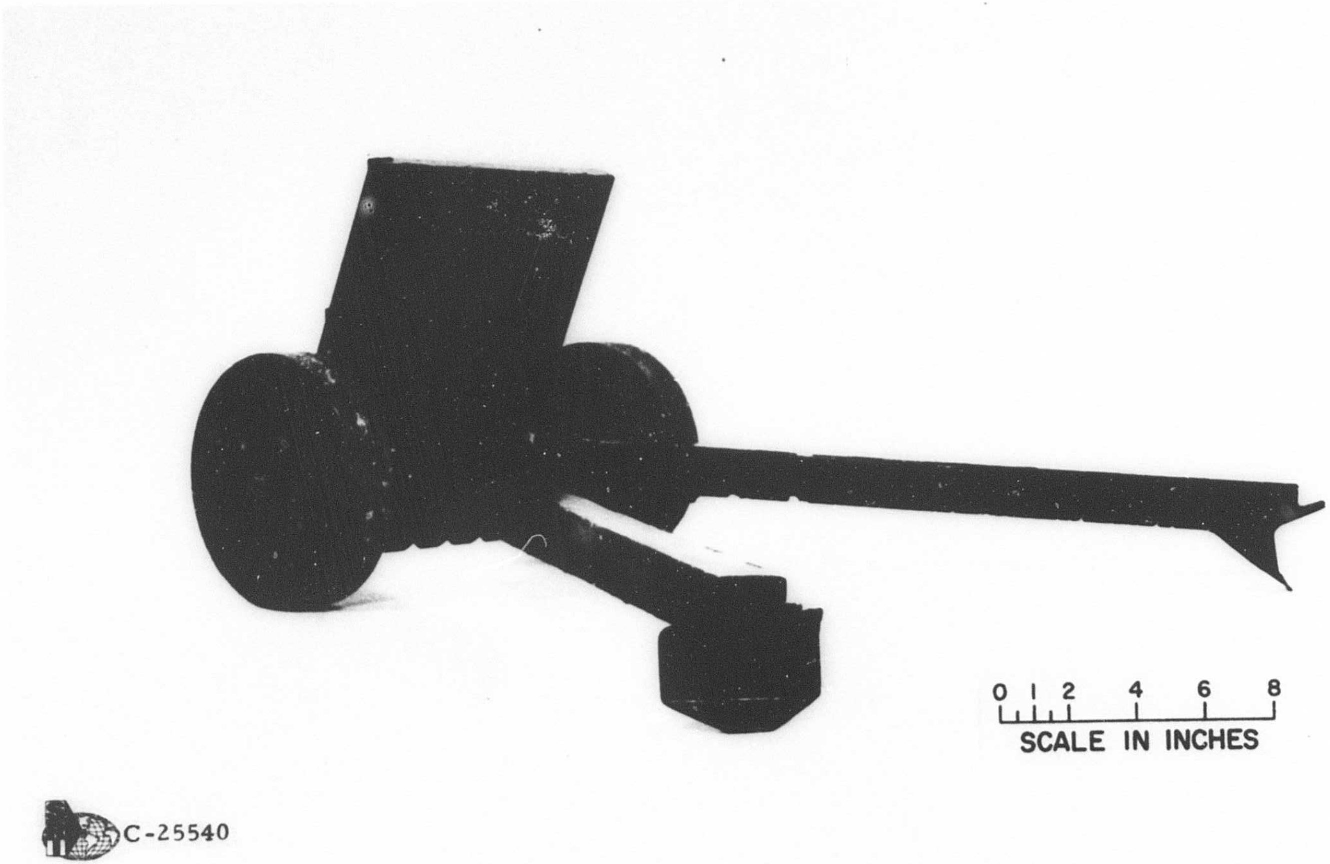


Figure 7. 1/5 Scale Model Of The Non-Recoiling Parts Of A Howitzer

prototype results. A transit with cross hairs providing a stationary reference measured residual horizontal and vertical displacements of the prototype howitzer to the nearest 1/100 of an inch. The author read a ruler through this transit after each shot. Rotations were measured by the gun crew to the nearest 1/10 of a mil by using a gunner's level. Three to four different test locations or "set-ups" were made with 5 to 6 rounds being expended at each location before relocating. All rounds fired water projectiles in zone 5 with an elevation angle of approximately 25° to pass the load directly through the spades of a 105 m.m. M2A2 howitzer. A picture of the cannon at the test site can be seen in Figure 8.

The 1/5 geometrically scaled replica model used in the comparison properly scaled the geometry in this problem and the inertial properties of the non-recoiling howitzer parts. A square wave pulse applied by the model loading device simulated the zone 5 loading history with a force of 280 pounds and a duration of 34 milliseconds. Because the test was conducted under field conditions and with both model and prototype in the same soil, no scaling of soil layering effects was achieved as discussed in Section III. One only expected results to correlate within 50% as was demonstrated in our Phase I effort. Horizontal deflections and rotations in the model were measured respectively to the nearest 1/1000 of an inch and 1/6 of a mil by using two 1/1000 of an inch dial gages spaced 6 inches apart. A 1/100 of an inch ruler measured the vertical deflection.

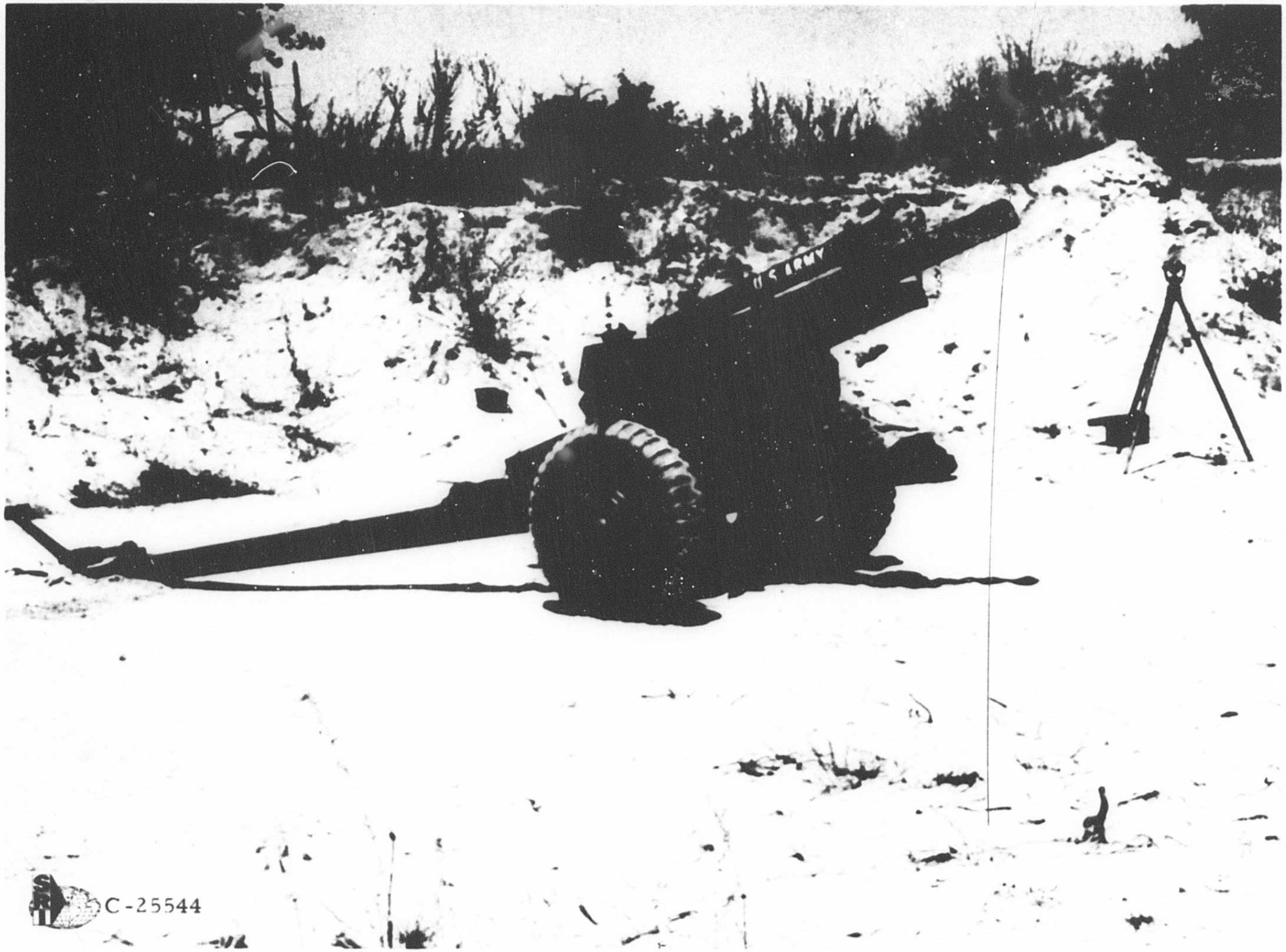


Figure 8. Howitzer At The Sand Test Site

The data from the sand tests are plotted in Figure 9, and correlation is relatively poor as could be expected from tests in sand. The author always plots total deflection or rotation versus shot number (not incremental deflection or rotation) as this procedure results in a better graphical averaging process. Incremental deflection or rotation between the various shots may be obtained from the slope of the curve. All deflections are plotted in prototype values. In particular, one should note the huge scatter that occurred between results of different "set-ups". Usually tests in sand exhibit much less scatter. The author believes much of the scatter can be attributed to the state of stress in the ground being close to that state of stress required to failure the soil from the dead weight of the weapon. Sand with no moisture is a very weak medium and the importance of gravitational effects was demonstrated when the gun crew attempted to tow the howitzer up a sand hill with a weapons carrier. The gun and vehicle mired down, and we chose an alternate test site. Although the author overlooked this event at the time, it does demonstrate how gravitational effects were significant at the sand test site.

All prototype or model tests were completed on any one given day, but the model and prototype tests were not both conducted on the same day. This reason accounts for the difference in moisture content noted in Figure 9. The author realizes moisture content plays a key role, but he does not feel it explains the discrepancy between

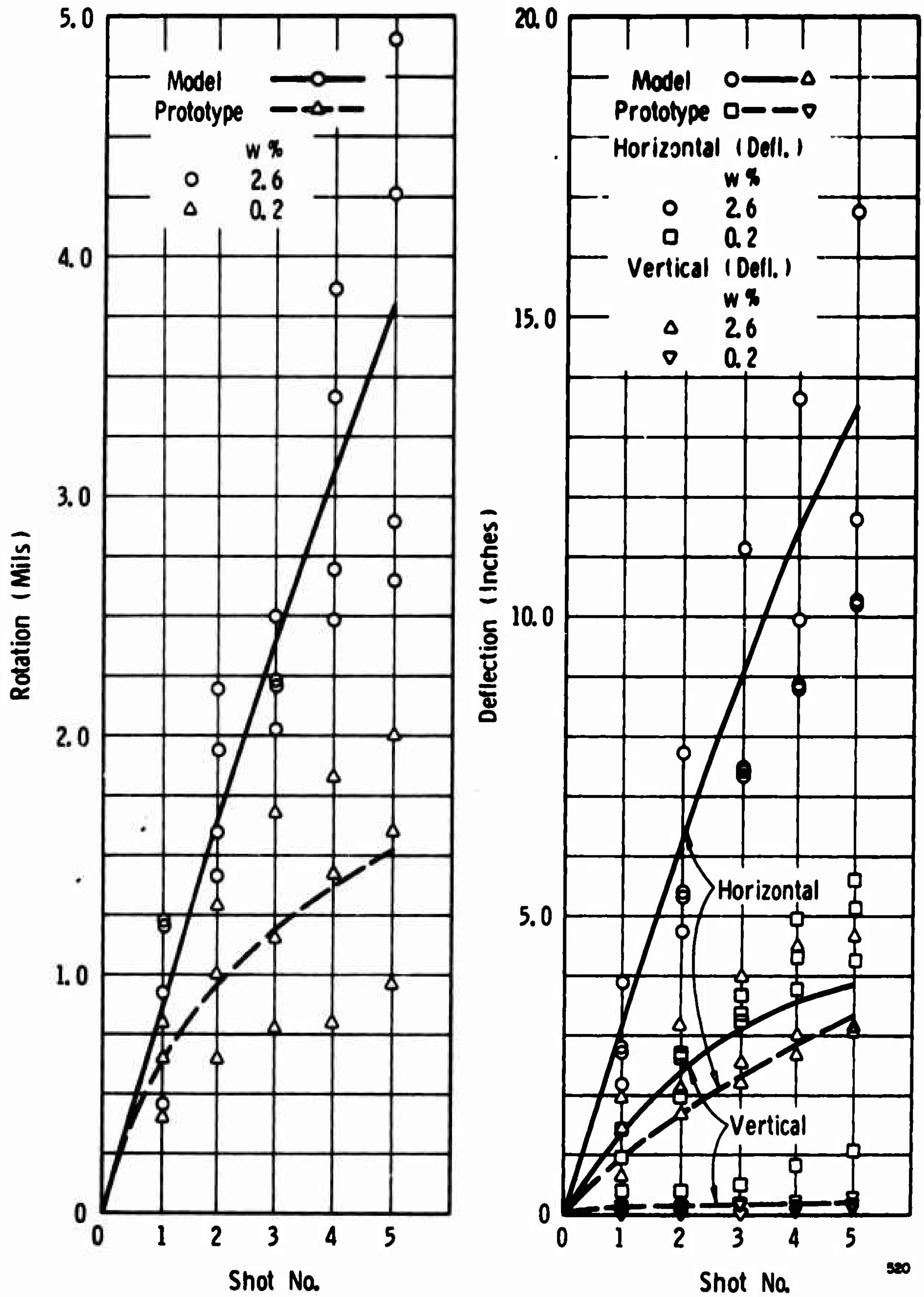


Figure 9. Model-Prototype Sand Comparison

model and prototype results, as a wet sand should be stronger than a dry sand and these results indicate the opposite trend.

The author feels that the non-scaling of soil layering effects caused soil pore pressures to be prematurely dissipated and soil gravitational effects to be distorted as described in Section III, with the expected result being a poor correlation. This phenomenon is more pronounced in sand than in clay. Actually, model soil conditions simulate a different prototype soil having a different degree of compaction.

Of added interest is a comparison between the prototype howitzer residual deflections and rotations when the wheels are locked and unlocked. Our model simulated a howitzer with its wheels unlocked and free to roll. Initially the author held prototype test firings with the wheels inadvertently locked. After this initial group of firings with locked wheels, the author realized the wheels had been locked when he reviewed the results. Thus, a new series of prototype sand firings were held with the wheels unlocked. Plotted in Figure 10 is a comparison between deflections and rotations obtained from firings with locked wheels to those obtained from firings with unlocked wheels.

Model Prototype Comparison In Clay

The clay site employed in our model prototype comparison (located here on the Institute grounds) consisted of a fat, black, organic,

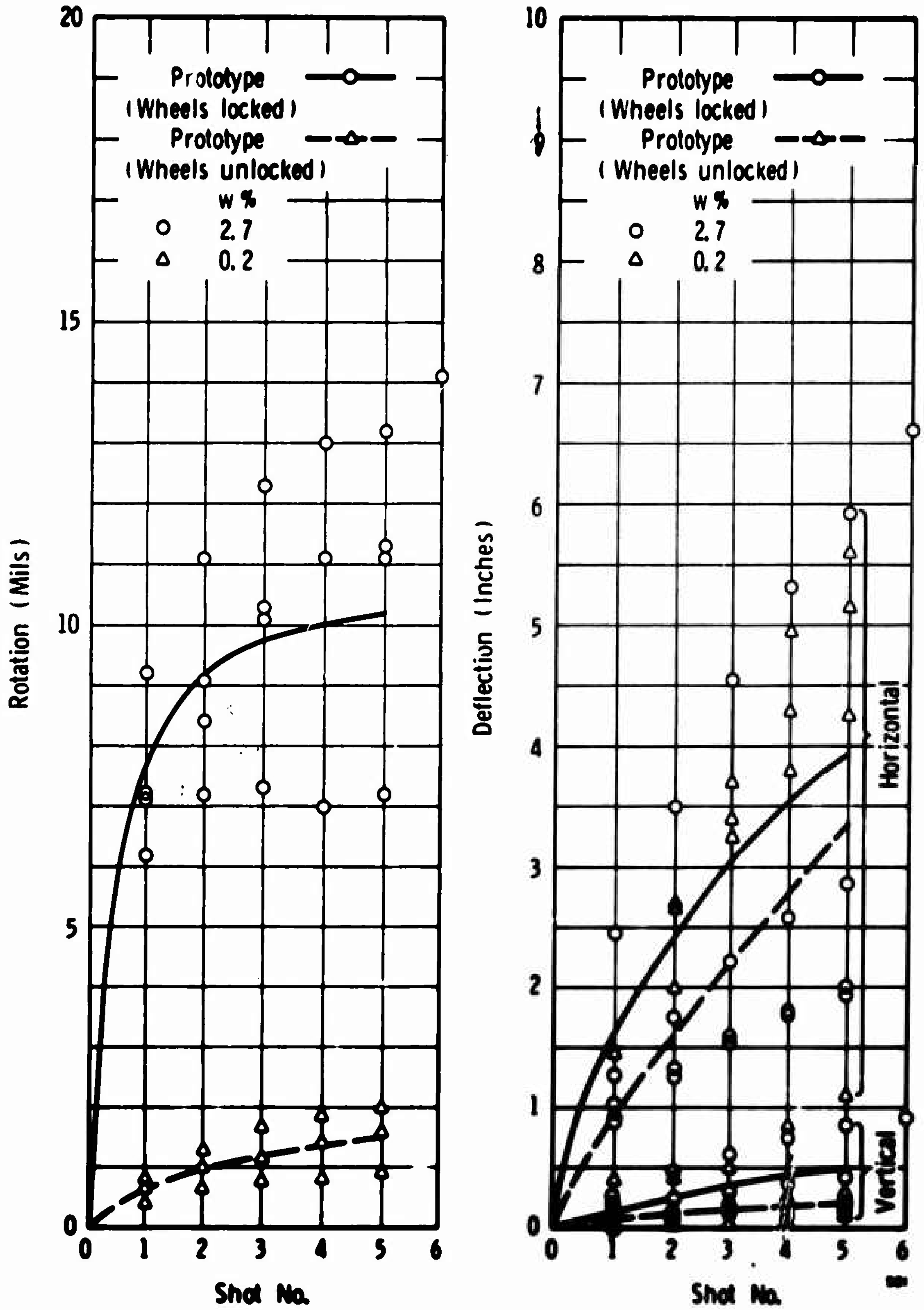


Figure 10. Comparison Of Howitzers With Locked And Unlocked Wheels

expansive clay, locally termed Houston Black. The soil conditions are summarized in the appendix. Horizontal displacements, vertical displacements and angular rotations were measured after each shot in the same manner that we measured prototype and model motions at the sand site. The prototype gun employed in the comparison at the clay site was a M2A2, 105 m.m. howitzer, and the same 1/5 geometrically scaled replica model was used at both sites. Only the intensity of loading differed as we fired in zone 7 at the stronger clay site. A square wave pulse applied by the model loading device simulated the prototype zone 7 loading history with a force of 420 pounds for a duration of 37 milliseconds. The accuracy of measurements are identical to those at the sand location. All howitzer rounds fired water projectiles in zone 7 with the barrel oriented to pass the load directly through the spades. A picture of test firings at the clay site can be seen in Figure 11. Because the test was conducted under field conditions with the model and prototype in the same soil, no scaling of soil layering effects was achieved as has been discussed. Nevertheless, one expects results to correlate better in the clay than at the sand site, as the layering effects are more pronounced in sand (see Section III).

The results from tests at the clay site are plotted in Figure 12 where total deflection and rotation are presented as functions of shot number. Very little scatter exists between different prototype or model "set-ups". The model results had to be obtained from a graphical

Figure 11. Howitzer At The Clay Test Site

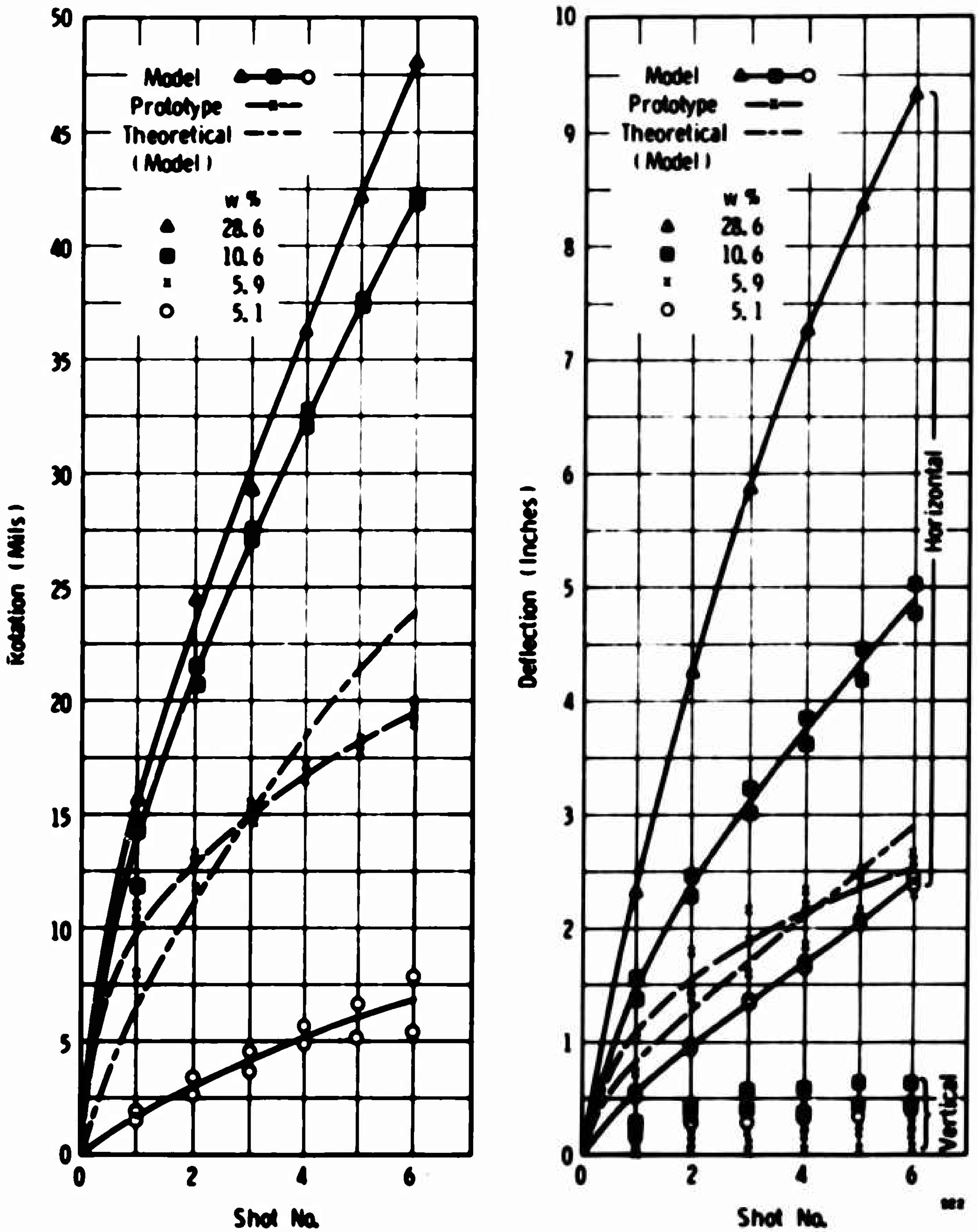


Figure 12. Model-Prototype Clay Comparison

construction of deflection or rotation versus water content, Figure 13. Rain modified our soil conditions after the prototype firings and before the model tests. Therefore, in Figure 12, one notes the results from three series of model tests at moisture contents of 5.1%, 10.6%, and 28.6%. This plot of model deflections and rotations versus shot number for different water contents illustrates the importance of moisture content. In Figure 13, the author plotted deflection or rotation versus water content for each shot. From Figure 13 he then obtained the appropriate model deflections at the water content of the prototype firings. The correlation between model and prototype results is good, especially when one considers that a graphical construction was required to obtain the results.

Summary

In this section we have presented a comparison between prototype results with locked and unlocked wheels, a contrast between model deflections and rotations in clay at different moisture contents, and a correlation between model and prototype results in both sand and clay. The correlation in clay is good; whereas, the correlation in sand is poor. Probably the lack of agreement in sand can be attributed to soil layering effects causing soil pore pressures to be prematurely dissipated and soil gravitational effects to be distorted as described in Section III. Definitely the dead weight of the howitzer (weapon gravi-

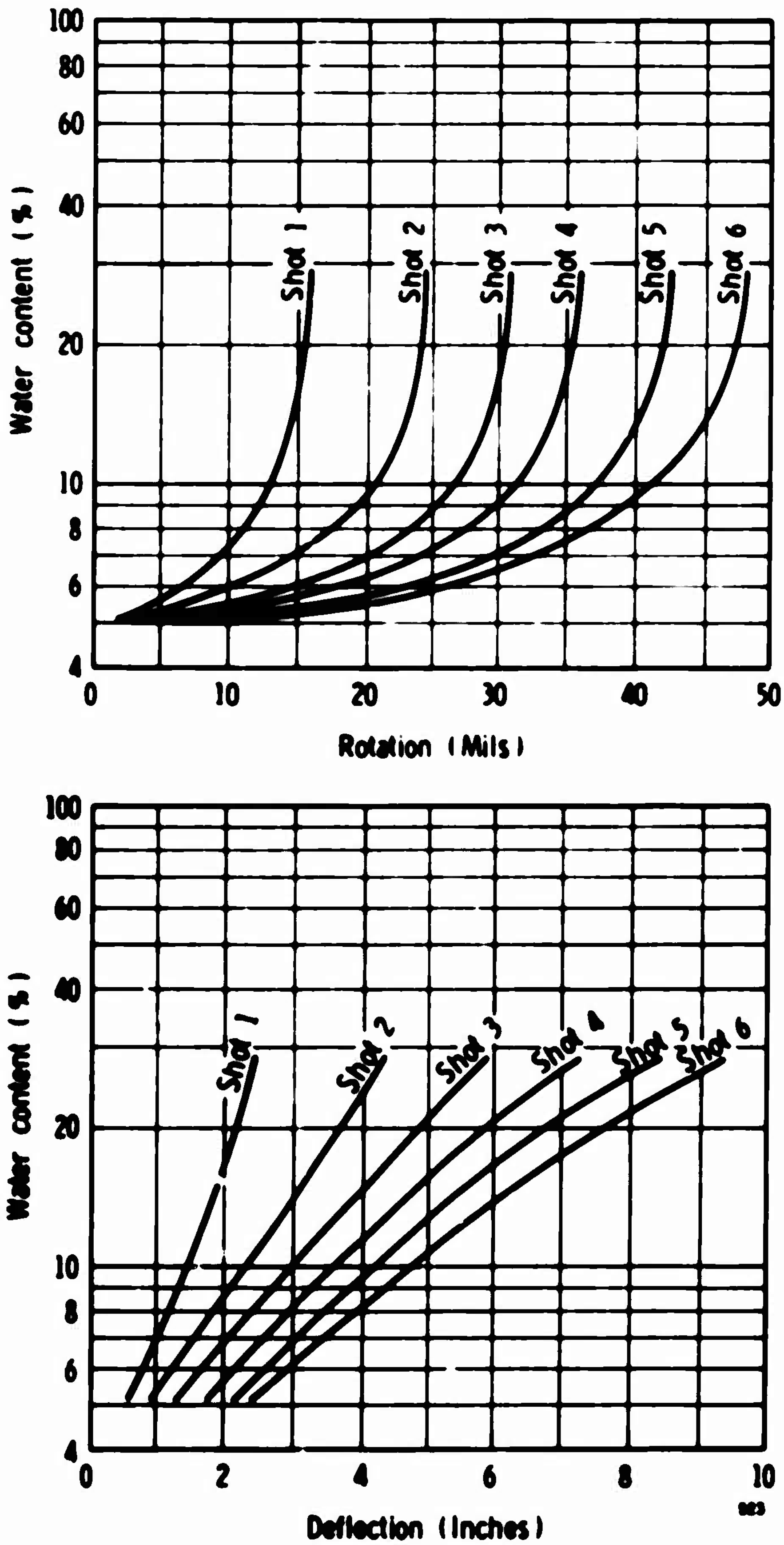


Figure 13. Moisture Content Vs Deflection Or Rotation At Clay Site

tational effects) played some role in the lack of correlation in sand. When we test anchoring elements (stakes and spades) in sand, as we are scheduled to do in Phase III of our program, the dead weight of the anchoring elements should be insignificant. An additional correlation between 1/3 and 1/5 scale model spades in clay is presented in Section VII.

V. DYNAMIC RESPONSE OF HOWITZERS

A simple elastic analysis on a system with one degree of freedom can illustrate qualitatively (not quantitatively) the behavior of a soil foundation. This does not imply that an elastic analysis is valid for our problem; it does offer insight into the qualitative behavior of a foundation. Assume the soil can be represented by a spring-mass system as in Figure 14. The spring in the analysis is linearly elastic in compression;

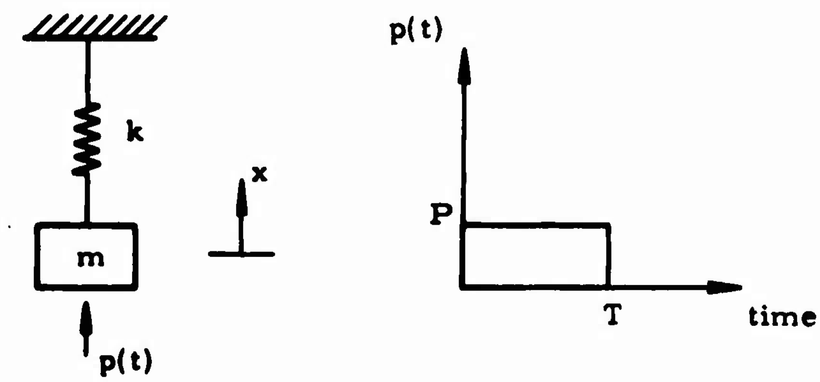


Figure 14

SINGLE DEGREE OF FREEDOM ELASTIC SYSTEM

however, it is infinitely stiff when attempting to rebound. A square wave pulse is applied to the mass. Such a model crudely represents the non-recoiling parts of a howitzer foundation being loaded by firing the weapon. From dynamic equilibrium one obtains for the maximum deflection of the spring:

$$X_{max} = \frac{2P}{k} \sin\sqrt{\frac{k}{m}}\ {}^{T}/_{2}$$

provided $\sqrt{\frac{k}{m}}\ {}^{T}/_{2} \ll {}^{\pi}/_{2}$

If the angle, $\sqrt{\frac{k}{m}}\ {}^{T}/_{2}$, is small, the impact analysis result when an initial velocity is imparted to the mass asymptotically approaches the more precise proceeding equation. An impact analysis yields:

$$X_{max} = \frac{P\quad T}{k^{1/2}\ m^{1/2}}$$

If the load duration is very long, one obtains a quasi-static result.

$$X_{max} = \frac{2P}{k}$$

provided $\sqrt{\frac{k}{m}}\ {}^{T}/_{2} \geq {}^{\pi}/_{2}$

By plotting natural frequency, $\sqrt{\frac{k}{m}}$, multiplied by the load duration against deflection, a plot is obtained as shown in Figure 15.

This plot illustrates several things. If the duration of the load is long compared to the natural period of the foundation, one discovers that the deformation is only a function of soil strength, k, and load level, P. Such a result would place one in a quasi-static analysis region. In this region, mass is a relatively insignificant parameter and the dynamic residual displacement would be directly proportional to static displacement.

In another region the duration of the loading is short compared to the natural period of the foundation. The deflection then becomes a

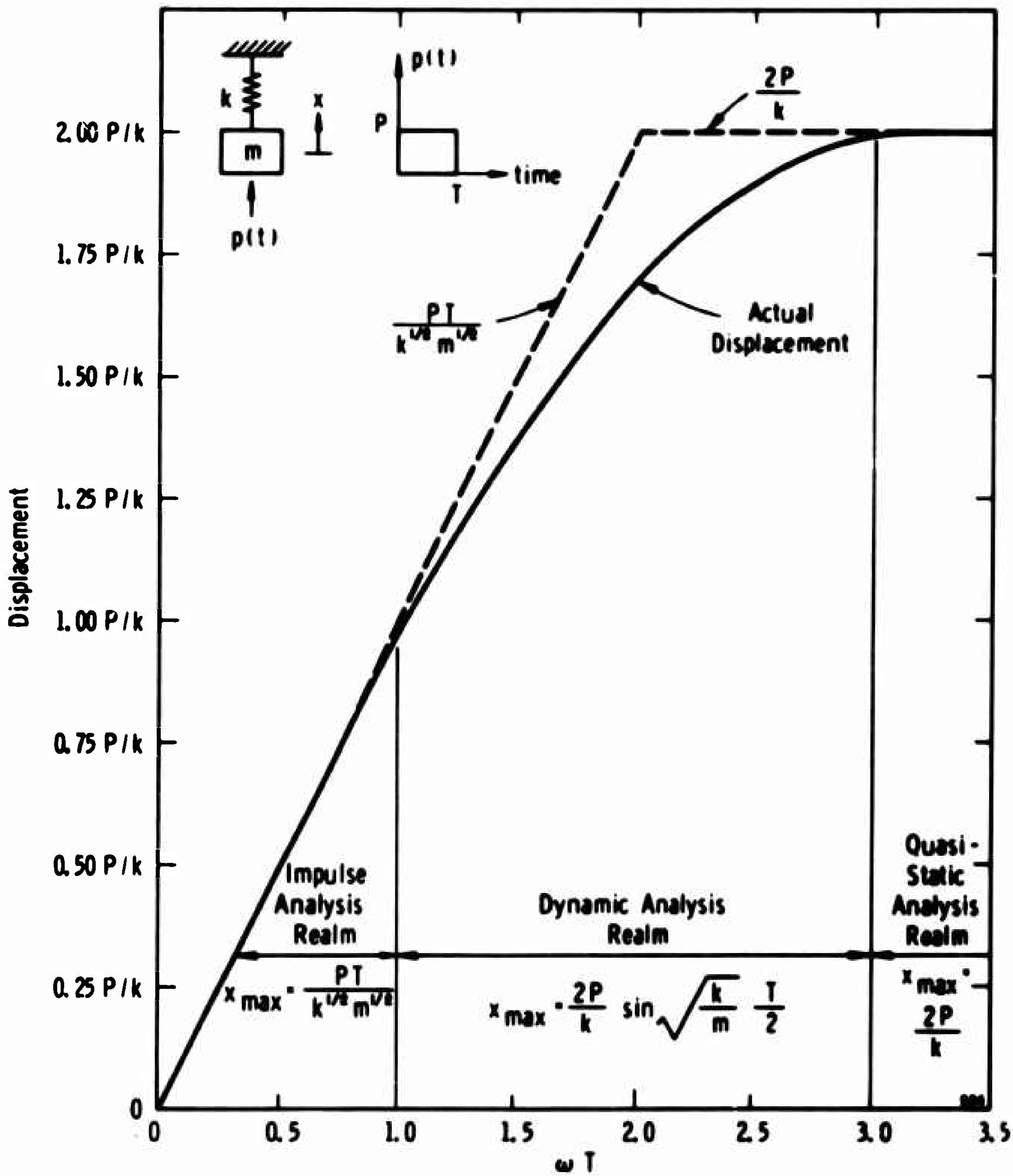


Figure 15. Dynamic Displacement Versus Frequency Curve For A Single Degree Of Freedom Elastic System

function of impulse (P x T), the foundation mass, and the strength of the soil. In this region, an impulse analysis applies, and the deflection is a function of the area under the applied force-time history. The recoil mechanism in artillery pieces would not alleviate displacements or rotations for a howitzer fired in this region. A gun that did not recoil would experience exactly the same deflections. In a one-degree-of-freedom system, an impulse analysis represents an upper bound on deflections. Ideally a recoil mechanism extends the duration of loading sufficiently to place the response in a quasi-static analysis region or less ideally, the dynamic analysis region.

The narrow third realm or region between the impulse and quasi-static regions represents a region that might be labeled the dynamic analysis region. In this realm the deflections are dependent upon the duration of loading, the magnitude of the load, the mass, and the soil strength.

While taking model measurements, the author conducted additional tests to determine if the response of artillery pieces fell in an impulsive region, a dynamic region, or a quasi-static region. To experimentally determine if the response is in a quasi-static region, one simply repeats a model test with the duration of loading increased and the load level, mass, and soil strength kept constant. One tests to determine if the response is in an impulsive region by repeating a model test with the duration decreased, the magnitude of the load in-

creased in a manner that keeps load level times duration constant. In these tests, the mass of the foundation is not modified, and the soil strength is kept the same. If the response does not fall in either the quasi-static or impulsive region, the response lies in the dynamic analysis region. Should the response fall in the quasi-static region, only two variables (load level and soil strength) are significant. Should the response lie in the impulse region, three variables (impulse, mass, and soil strength) are important. Four variables (load level, duration, mass, and soil strength) are all significant in the dynamic analysis region. The author tested to determine if any parameters could be eliminated and in which realm a 105 m.m. howitzer foundation belonged. Before discussing the test results, a few comments on the coupled response of foundations are in order.

The rotations and deflections of an artillery piece are coupled in such a manner that the foundation can vibrate either in-phase or out-of-phase, as indicated in Figure 16.

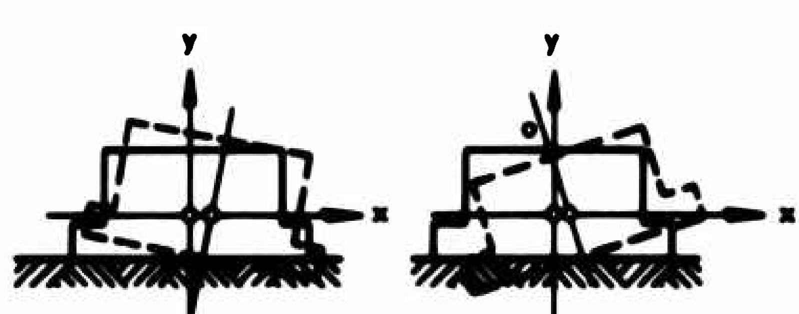


Figure 16

FOUNDATION VIBRATIONS

Barkan, in what is probably the foremost text on soil dynamics[10], indicates that horizontal displacements and rotations are coupled; however, the vertical displacement is generally uncoupled or can accurately be assumed to be uncoupled. One must note that Barkan only considers industrial vibrating or impacting foundations where little residual motion can be tolerated. Our weapon foundations exhibit significant residual motion with each impact, and the author has observed that the vertical displacement is coupled with the horizontal translation and rotational response. This observation based on experimental results will be elaborated upon later in Section VII.

Another observation, demonstrated in Barkan, is that for a two-degree-of-freedom elastic system, the two principal natural frequencies have roots determined by the two limiting frequencies. If one selects f_ϕ to represent the rotational limiting frequency of the foundation when the resistance of the soil to shear is very large, and f_x to represent the translational limiting frequency when the resistance to rotation is large, then the lower of the two natural frequencies, associated with in-phase-vibration, is lower than both of the limiting frequencies, and the larger natural frequency, associated with out-of-phase vibration, is larger than both limiting frequencies. This observation is important in understanding results to be discussed later in this section.

The background on the dynamics of foundations presented in this section helps to interpret the results from a series of model tests investigating the importance of mass, mass distribution, load level, and duration on the response of artillery foundations. These model tests, performed by loading a 1/5 scale model of a 105 m.m. M2A2 howitzer with a square wave pulse, used zone 7 charge levels at the clay test site and zone 5 levels at the sand test site. The line of action of the load always passed through the spades of the howitzer. A picture of the model being loaded may be seen in Figure 17. We investigated two different soils under two different moisture conditions. The clay site and sand site used in the model-prototype comparison were employed for tests performed on a dry sand, a wet clay, and a dry clay. A new sand site located on the Institute grounds was used for wet sand tests. The properties of the soils are summarized in the Appendix. Residual vertical displacement, horizontal displacement, and rotations were recorded. All results exhibited little scatter except those obtained in the weakest soil, dry sand.

A typical test proceeded as follows:

1. Implant the 1/5 scale model in the test soil
2. Load the model with a zone 5 charge ($P = 280$ lbs., $T = 34$ m.s.) at the sand sites, or with a zone 7 charge ($P = 410$ lbs., $T = 37$ m.s.) at the clay site.
3. Measure the residual horizontal displacement, vertical displacement, and rotation.

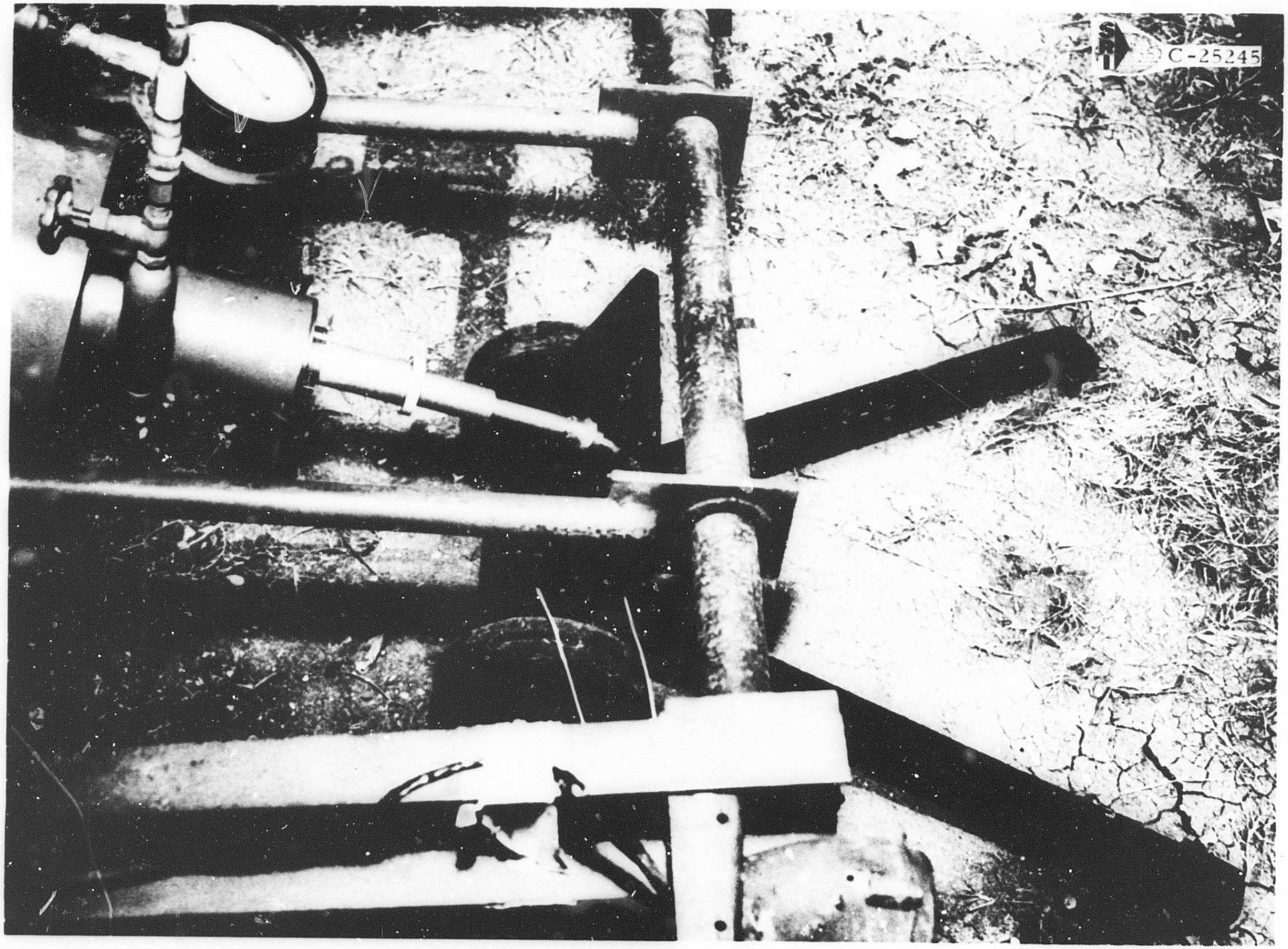


FIGURE 17. DYNAMIC LOADING OF A FIFTH-SCALE HOWITZER

4. Reload the model loading device and repeat the loading without replanting the model. Measure the same residual motions.

5. Perform a series of from three to five shots using this procedure. Then replant the model at a new undisturbed location and repeat the tests.

6. Measure the soil's moisture content and perform penetrometer tests to roughly account for differences in field conditions.

7. After performing a series of tests at regular charge levels, conduct a new series by reducing the duration of loading and increasing the load level while maintaining the impulse, the area under the applied load time history, constant. If the resulting displacements and rotations are identical to those experienced by the model under normal zone 5 and 7 conditions, the foundation is in the impulse region.

8. Finally conduct a series of tests to determine if the response lies in the quasi-static region. Conduct these firings by maintaining zone 5 load levels in the sands (P = 280 lbs) and zone 7 load levels in the clay (P = 410 lbs); however, lengthen the duration of loading beyond regular zone 5 or zone 7 durations. If the resulting displacements and rotations are identical to those experienced by the model under normal loading conditions, the response of the foundation lies in the quasi-static realm.

9. If the results from the impulsive test series and the load duration series do not duplicate those experienced by the model under zone 5 or zone 7 conditions, then the response of the foundation lies in the dynamic response region.

The resulting residual rotations, horizontal deflections, and vertical deflections are plotted versus shot number for dry sand, wet sand, dry clay, and wet clay, in Figures 18, 19, 20, and 21.

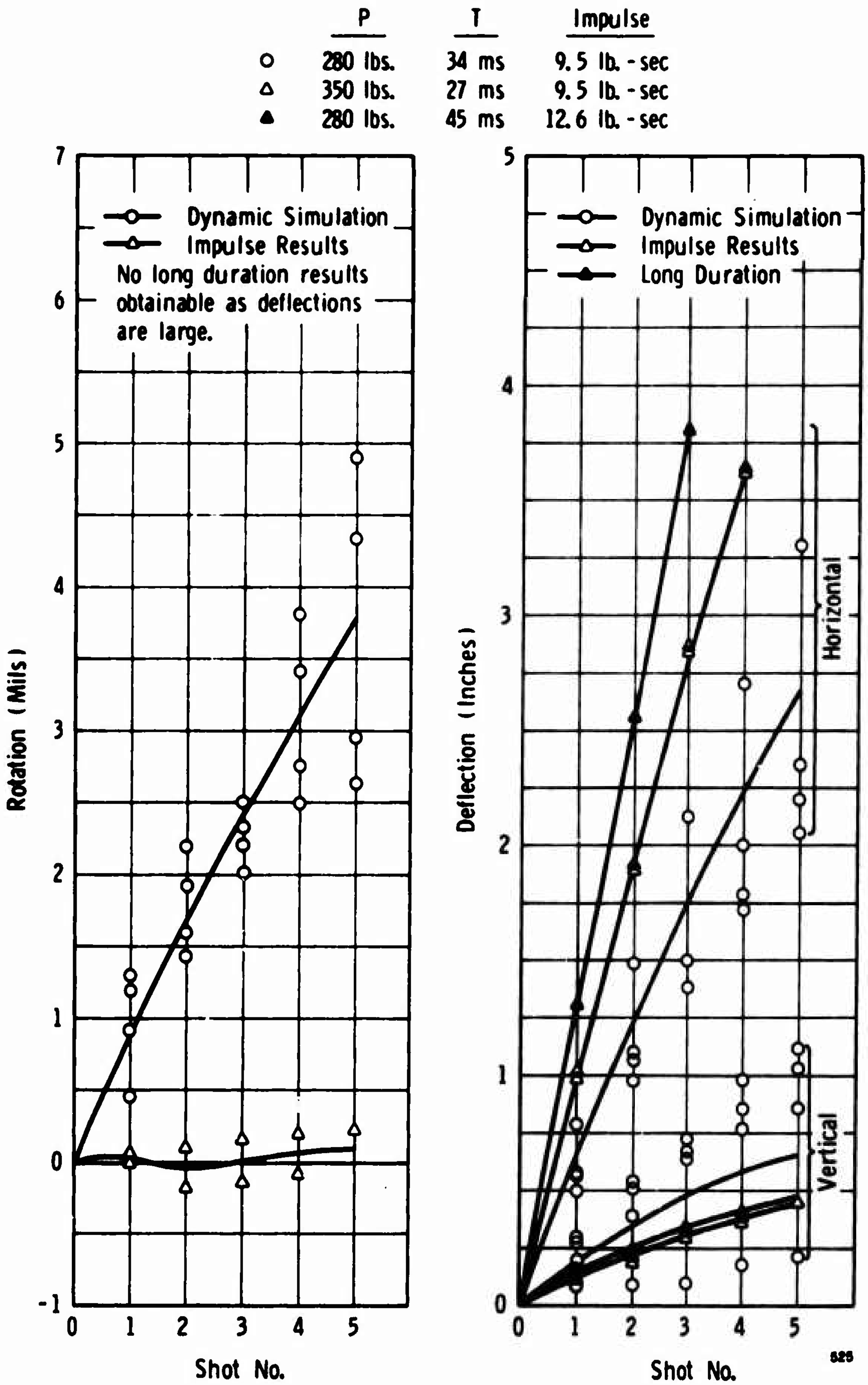


Figure 18. The Influence Of Load Duration In Dry Sand

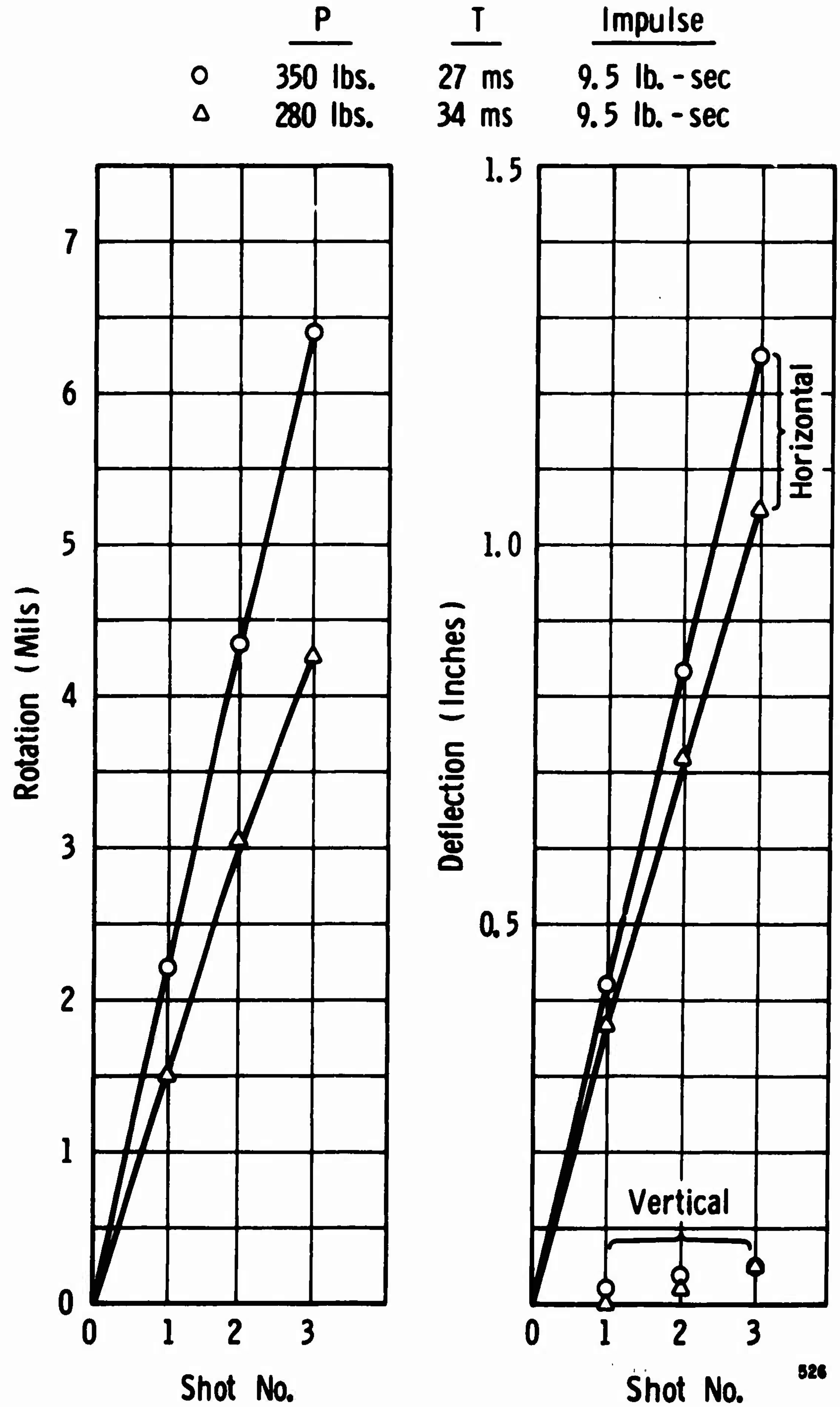


Figure 19. The Influence Of Load Duration In Wet Sand

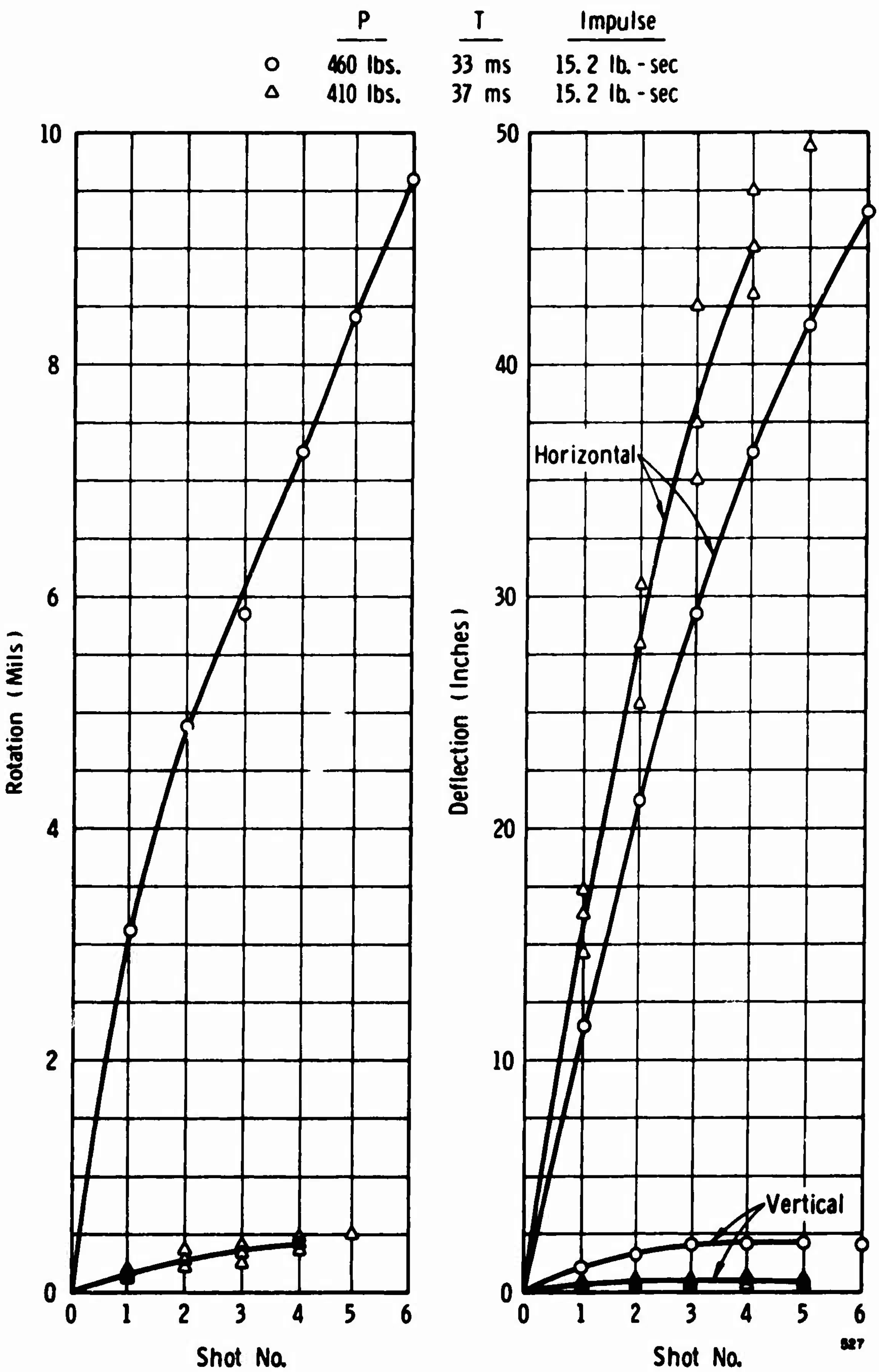


Figure 20. The Influence Of Load Duration In Dry Clay

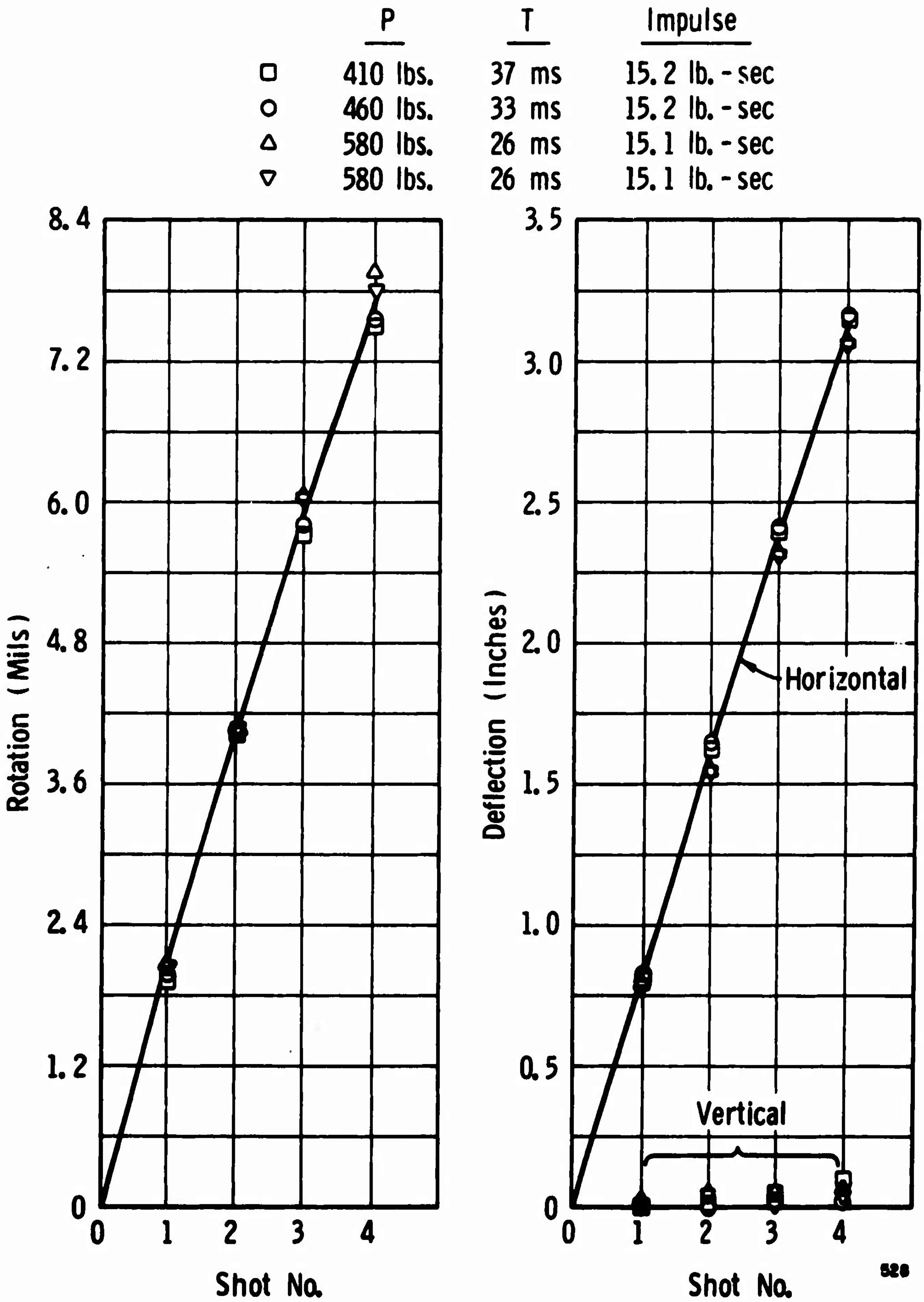


Figure 21. The Influence Of Load Duration In Wet Clay

The horizontal displacement and rotations were measured very accurately to the nearest 1/1000 of an inch or nearest 1/6 of a mil by using one-inch stroking dial gages. The vertical deflections are recorded to the nearest 1/100 of an inch; thus, they are less accurate and are not plotted on a scale that would misrepresent the accuracy. Under all circumstances, the long duration test series produced excessive deflections far beyond the ability of our instrumentation to measure the results. This observation strongly indicates that the response of artillery foundations do not lie in the quasi-static realm. A quasi-static analysis of the displacements of howitzer foundations is not justified. When one realizes that the natural period of most foundations is long when compared to the duration of loading even with a recoil system, this observation should surprise no one.

Many more tests were made in dry sand than in the other soils, as considerably greater scatter occurred in dry sand, the most difficult medium with which to work. Dry sand was an unusually difficult media, as the dead weight of the model created a state of stress in the ground that nearly failed the soil. All the other soil conditions exhibited next to no scatter.

A comparison of a more impulsive loading to the regular zone 5 loading in sand, or zone 7 loading in clav, provides major interest. In the dry sand, as shown in Figure 18, a more impulsive loading caused greater horizontal deflections, but significantly less rotation.

The rotation is so small that virtually no rotation occurred in the dry sand under a more impulsive load. This result indicates that the response of the foundation was out-of-phase in such a manner that a more impulsive load transferred additional energy into sliding and less into rocking the foundation. For this foundation condition, a recoil mechanism actually reduced weapon stability by extending the duration of the impulse. Definitely the response of the foundation for this soil condition lay in the dynamic analysis range.

The author does not maintain that recoil mechanisms would always reduce weapon stability. In the wet sand, Figure 19, a more impulsive load increased rotations while also increasing deflections. Under these conditions, the response of the foundation was in-phase, and a recoil mechanism would increase weapon stability. Again the foundation response fell in the dynamic analysis realm.

In the dry clay, Figure 20, a more impulsive loading gave greater rotations while reducing deflections. This result can only be caused by the response being coupled and out-of-phase. Again the recoil mechanism would increase weapon stability. Under this condition, the foundation response fell in the dynamic analysis realm.

Of particular interest are the results from the model loaded with a zone 7 charge in wet clay, Figure 21. A more impulsive load applied to the model yielded exactly the same deflections and rotations. This result demonstrates that a weapon without a recoil mechanism

would have undergone the same foundation motions as the recoiling gun. The response for this foundation condition lay in the impulsive region.

The more impulsive loading results are summarized in the following table.

Experimental Observations
On More Impulsive Loading

Soil	Rotations	Deflections	Phase	Analysis realm
Dry sand	reduced to nearly zero	increased	out-of-phase	dynamic
Wet sand	increased	increased	in-phase	dynamic
Dry clay	increased	reduced	out-of-phase	dynamic
Wet clay	not changed	not changed	can't determine	impulse

One can summarize the observations made in this section by saying that the foundation response of a howitzer is coupled, may be either in-phase or out-of-phase, and lies in either the dynamic analysis realm or the impulsive loading region. The results demonstrate that significant improvements can be forthcoming in the design of weapons that minimize rotations provided a good dynamic analysis procedure is developed. We have observed that a recoil mechanism can either increase or reduce weapon stability. Under other conditions the recoil mechanism complicates gun design, creates maintenance problems, and increases weapon costs without altering the response of a foundation. At other times the recoil is beneficial. A coupled multidegree of freedom dynamic foundation analysis is required to properly optimize the design of weapon foundations.

VI. DATA GATHERING PROGRAM

In Section V on howitzer response, we have seen that rotations and displacements depend upon mass, mass distribution, geometry in the problem, soil conditions, duration of loading, and load level. The resulting response of a howitzer is coupled, with the displacements and rotations interdependent. This behavior cannot be described by simple graphs, charts, monographs, or elementary analytical expressions. The proposals for the Phases I and II in our overall program expressed the view that a handbook would result containing rudimentary graphs, charts, monographs, and analytical expressions. The author is of the opinion that such a handbook cannot result, but a final Phase III report can contain firm analytical guidelines to be used in conjunction with data on stakes, spades, and other elements in a dynamic analysis of foundations. This dynamic analysis will be a nonlinear, coupled, multi-degree-of-freedom analysis for artillery foundations. With the use of computers, an analysis should result that would predict the rotations and displacements of a howitzer under various loadings in different soils. The design of this data gathering program reflects what the author considers to be an appropriate approach to developing a functional final report.

Computer Analysis of Howitzer Response

Since we are concerned with obtaining solutions to equations of motion for interconnecting bodies (the foundation and each anchoring

element) under impact loading, let us consider the form of these equations in rather general terms. We consider the elements and the foundation of the weapon as rigid. The foundation and the anchoring elements can be connected elastically. Only the planer problem is being considered in this illustration. We are interested in motion relative to the ground, which is represented by an inertial frame of reference. Coordinate systems are affixed to each body (the foundation and each anchoring element), with an origin at the center of mass of the particular body. This system is shown schematically in Figure 22.

If we properly choose the orientation of the body-fixed axes, they will be principal axes, and the bodies will possess inertial properties which are specified by their masses, m; their mass moments of inertia, I; and their geometry. In this case the angular momentum of a body is defined by:

$$\bar{H} = I\bar{\omega} \tag{1}$$

where $\bar{\omega}$ is the angular velocity of the body with respect to an inertial frame of reference.

If one wishes to obtain velocities and accelerations of points such as p_f and p_s, one assumes that these points are fixed with respect to the moving axes, o_f and o_s. With this restriction, the linear velocity of a point on each body is given by

$$\bar{V}_o = \bar{\dot{\rho}} + \bar{\omega} \times \bar{r} \tag{2}$$

and acceleration by

$$\bar{a}_o = \bar{\ddot{\rho}} + \bar{\omega} \times (\bar{\omega} \times \bar{r}) + \bar{\dot{\omega}} \times \bar{r} \tag{3}$$

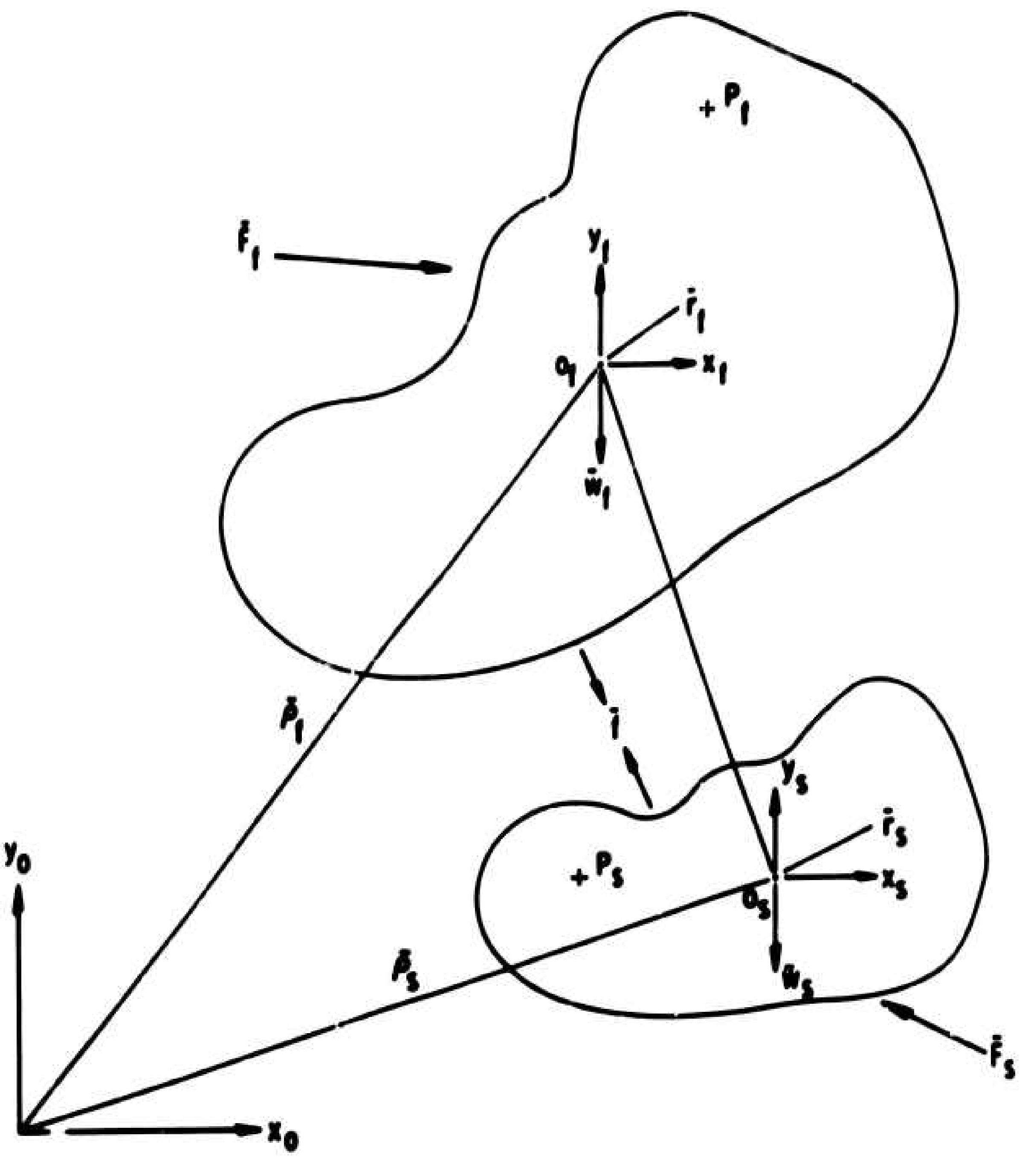


Figure 22. Coordinate System

Translational and rotational motions of the bodies are governed by Newton's laws of motion. These translational equations are:

$$m\ddot{\overline{\rho}} = \Sigma\,\overline{F} + \Sigma\,\overline{f} \qquad (4)$$

The equations of angular motion are:

$$\dot{\overline{H}} = I\dot{\overline{\omega}} = \Sigma\,\overline{L} \qquad (5)$$

where the $\overline{L}$ is an applied torque. Equation (5) applies whether angular momenta and torques are computed about a fixed point or a moving center of mass. For the latter case,

$$\overline{L} = (\overline{r} \times \overline{F}) + (\overline{r} \times \overline{f}) \qquad (6)$$

Because we are concerned with a multi-body problem, there are multi-sets of equations (4) and (5) to be solved, subject to specified initial conditions. Each equation (4) represents two degrees of freedom for each body, and each equation (5) represents one degree of freedom, giving a total of three degrees of freedom for each body. The foundation or body, f, has applied to it external forces $\overline{F}_f$ and a body force $\overline{W}_f$ in the $-Y_o$ direction, and forces of interaction between it and the anchoring stakes and spades of bodies, S. The bodies S (elements) feel internal forces, a body force, and external forces F_s with the ground.

By defining the dimensions and other characteristics of the components, a mathematical model may be chosen in which any stake or spade (body S) either is or is not considered.

The forces being considered in this analysis are all well defined with the exception of the external forces on the stakes and spades. The

weight and geometry of all components in the model are well known. Also well established are the external force, its duration, its orientation, and its line of action as applied to the foundation or body f. The internal forces between the body f and the bodies S are elastic and would only depend on the relative displacements and rotations of the co-ordinate systems associated with bodies f and S. The influence coefficients relating the relative displacements to the internal forces could be obtained either analytically or experimentally for a given artillery piece. Only the external forces on the stakes and spades or bodies S are undefined in this problem.

Data Acquisition Program

To complete the solution of our problem, horizontal deflections, vertical deflections, and rotations of anchoring elements must be obtained as functions of each other, the internal force, the internal moment, the internal angle of load application, the soil, and time. Our model loading devic loads anchoring elements as seen in Figure 23. The magnitude of the load, duration of loading, orientation of the load, and point of the load application can all be systematically varied, see Figure 24. Different stakes and spades may be attached to the device gripping the anchoring element. The major portion of this data gathering program is planned for our Phase III effort, although we are collecting data on spades in clay here in Phase II.

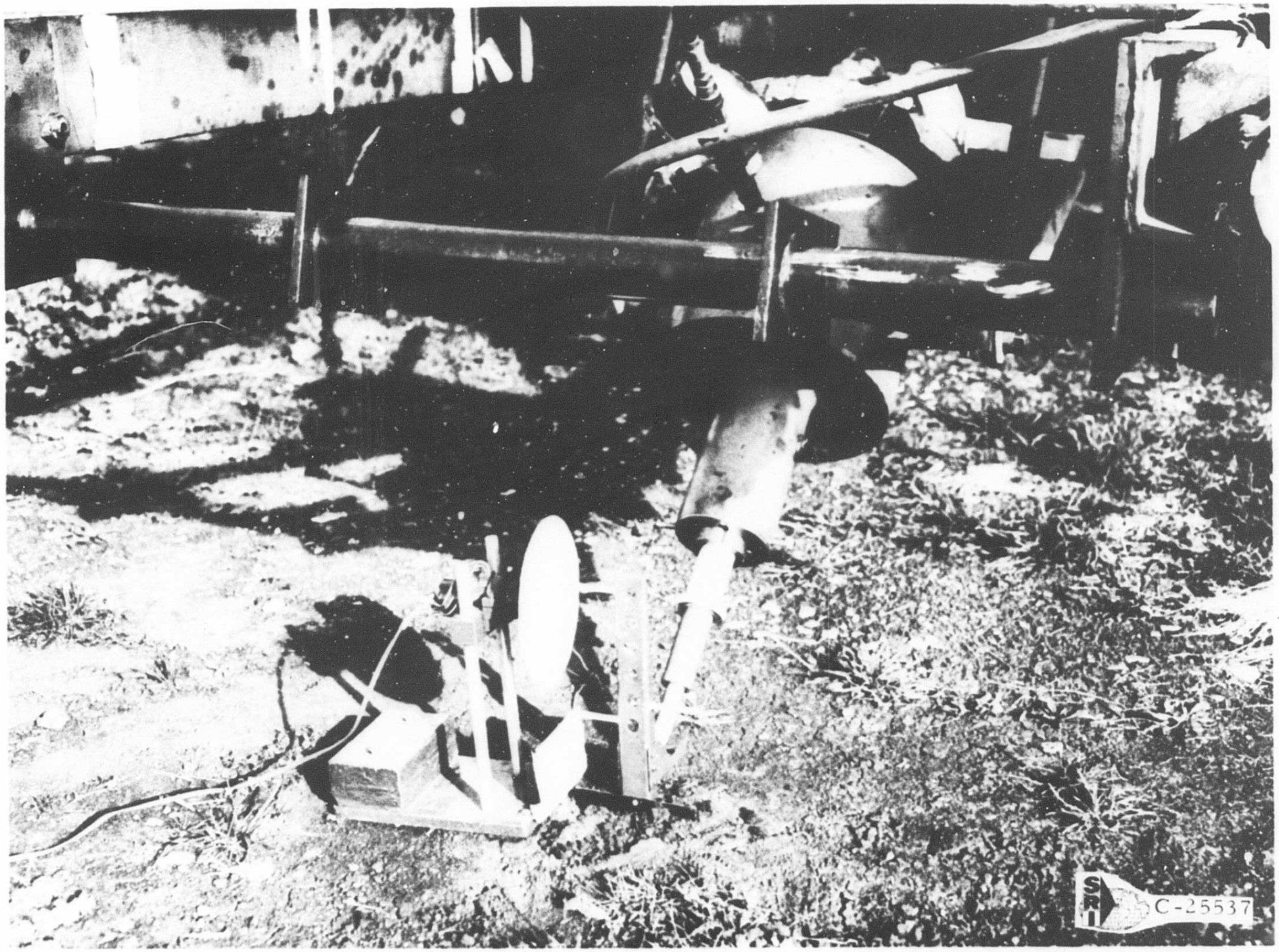


Figure 23. Model Loading Device, A Spade, And Instrumentation System

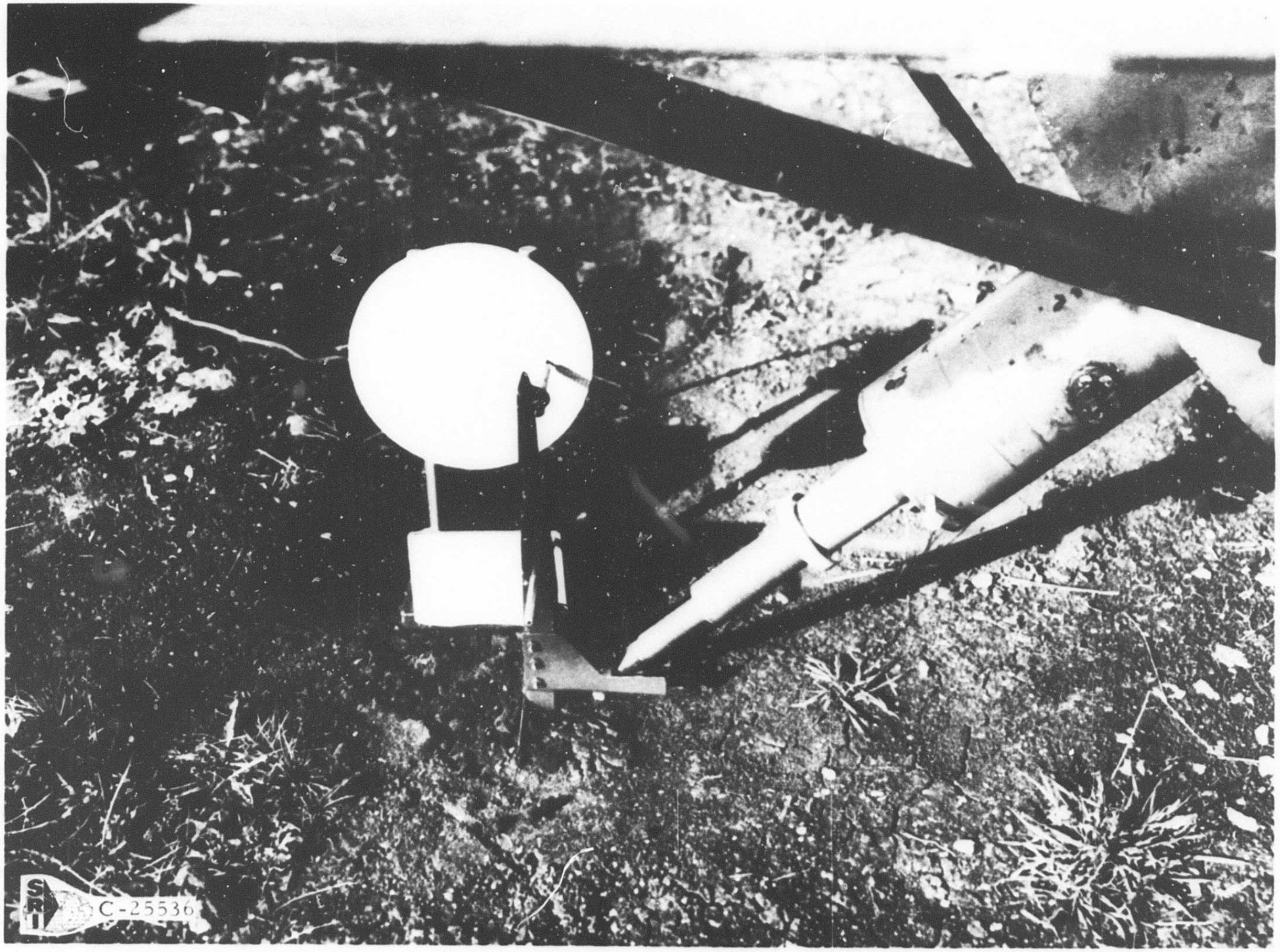


Figure 24. Close-Up Of Model Spade Being Loaded

Stakes are being investigated with three different depth to width ratios, and spades are being tested for four different depth to width ratios. The size of the elements are scaled down to approximately 1/4 the dimensions of current 105 and 155 m.m. anchoring elements. Three fluted stakes 5", 7", and 9" long are being studied, and spades are being studied for length to width ratios of 1/2, 1/3, 1, and 3/2. A picture of our model spades may be seen in Figure 25 together with the gripping device. To obtain results for other anchoring elements possessing the same relative geometry, one scales the res 's according to the modeling laws.

We will study these foundation elements in two different soils (cohesive soil and non-cohesive soil) under numerous (probably three) different moisture contents. The model loading device applies a constant force to each foundation element with the line of action of the force and the moment arm held constant during the loading of the stake or spade. Three different force levels; a force level creating a significant deflection of from 1/2 to 3/4 inch, another force causing a moderate deflection of 1/4 to 1/2 inch, and third force producing a small deflection of 1/8 to 1/4 inch; are applied to each anchoring element. The author cannot be more specific about the magnitude of the forces as the magnitude differs with soil conditions. The forces are applied to the spades at angles of 20, 30, and 40 degrees with the horizon and to the stakes at angles of approximately 6 degrees into the ground, 6 degrees out of

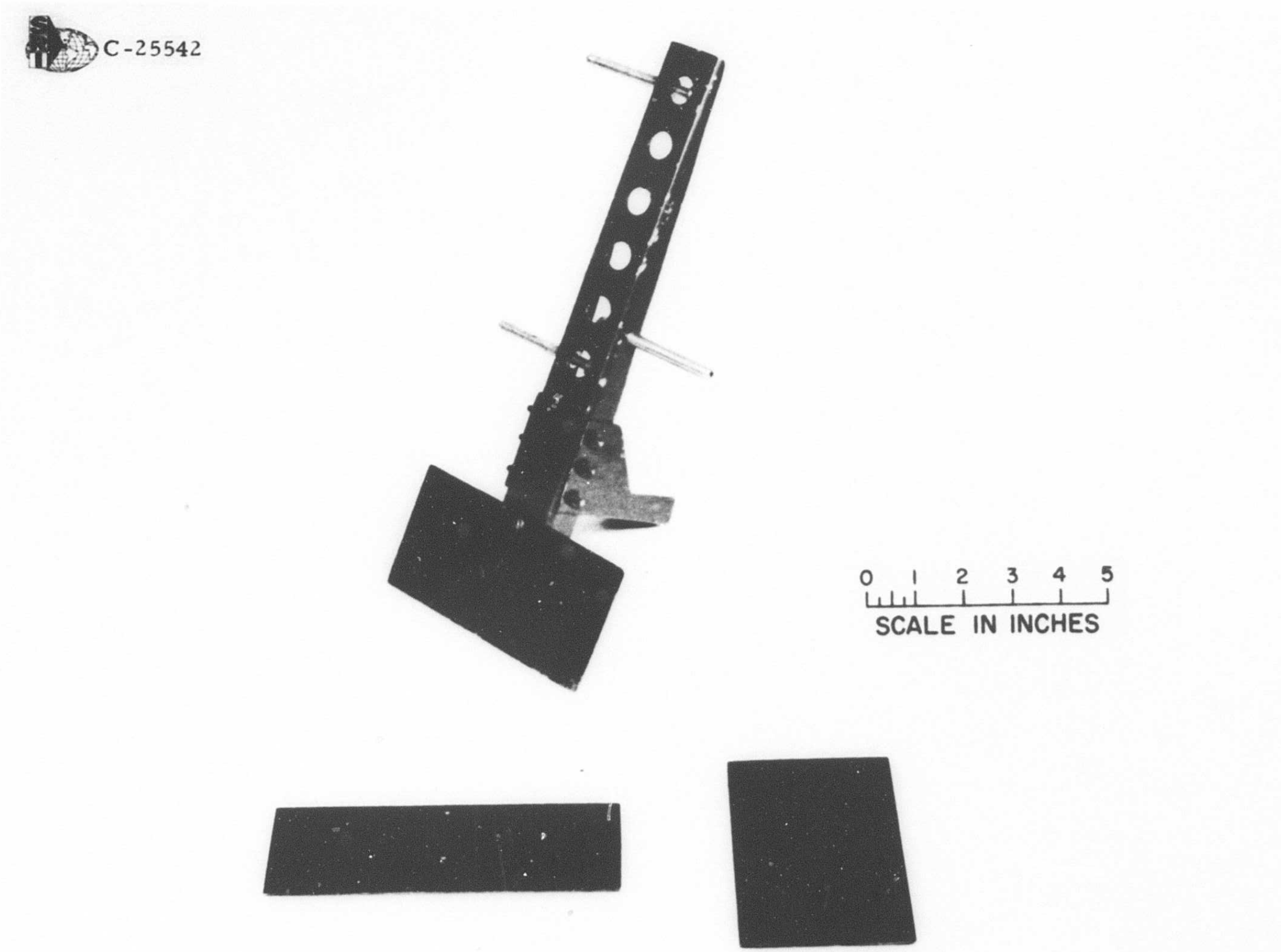


Figure 25. 1/4 Scale Spades And Gripping Device

the ground, and 16 degrees out of the ground. Four different moment arms apply different degrees of constraint to the anchoring elements. For a load applied at 20 degrees, the moment arm will be varied between 34% and 171% of the depth of the anchoring element; for a load at 30 degrees, the moment arm will be 22% to 108% of the depth; and for a load at 40 degrees, the moment arm will be 16% to 81% of the depth. A similar variation will be used with stakes. Three different durations of loading are employed in our data acquisition program. The durations vary from 25 m. s. to 42 m. s. in the simulation of recoiling loads. A very short duration impulsive loading will be used in Phase III. In summary, the following numbers and types of parameters are being considered:

Depth to width ratios stakes	3
Depth to width ratios spades	4
Soils	2
Moisture contents	3
Duration of loading	3
Angle of load application	3
Magnitude of force	3
Moment arm or degree of constraint	4

This series of experiments requires 4536 tests to cover all combinations and represents an extensive experimental program.

Instrumentation

Initially we had planned to instrument the test elements with three accelerometers to read vertical displacement, horizontal displacement and rotation. The accelerations were integrated twice electronically to obtain the displacements and rotations. We checked this procedure by comparing the electronically obtained residual displacements with measured residual displacements using dial gages. No correlation resulted as we overdrove our system. To remedy this situation, special amplifiers were required and might have been constructed. The author decided against constructing amplifiers, as the approach would have been expensive and the equipment too bulky for field work.

Several other schemes were considered such as measuring transient displacements through slide wire resistance change, photographic techniques, and inductance devices. All of these devices presented limitations for various reasons. Finally, we decided to measure transient displacements mechanically with spring loaded pencils marking revolving disks. A picture of this instrumentation in use may be seen in Figure 26. Small d. c. motors powered by the truck battery drive the disks in Figure 26 at approximately 170 rpm's. The spring loaded pins in the figure trace the displacement time history of the dynamically loaded element on the rotating disk. To compute rotations, one uses the horizontal displacement time history traced with a pen

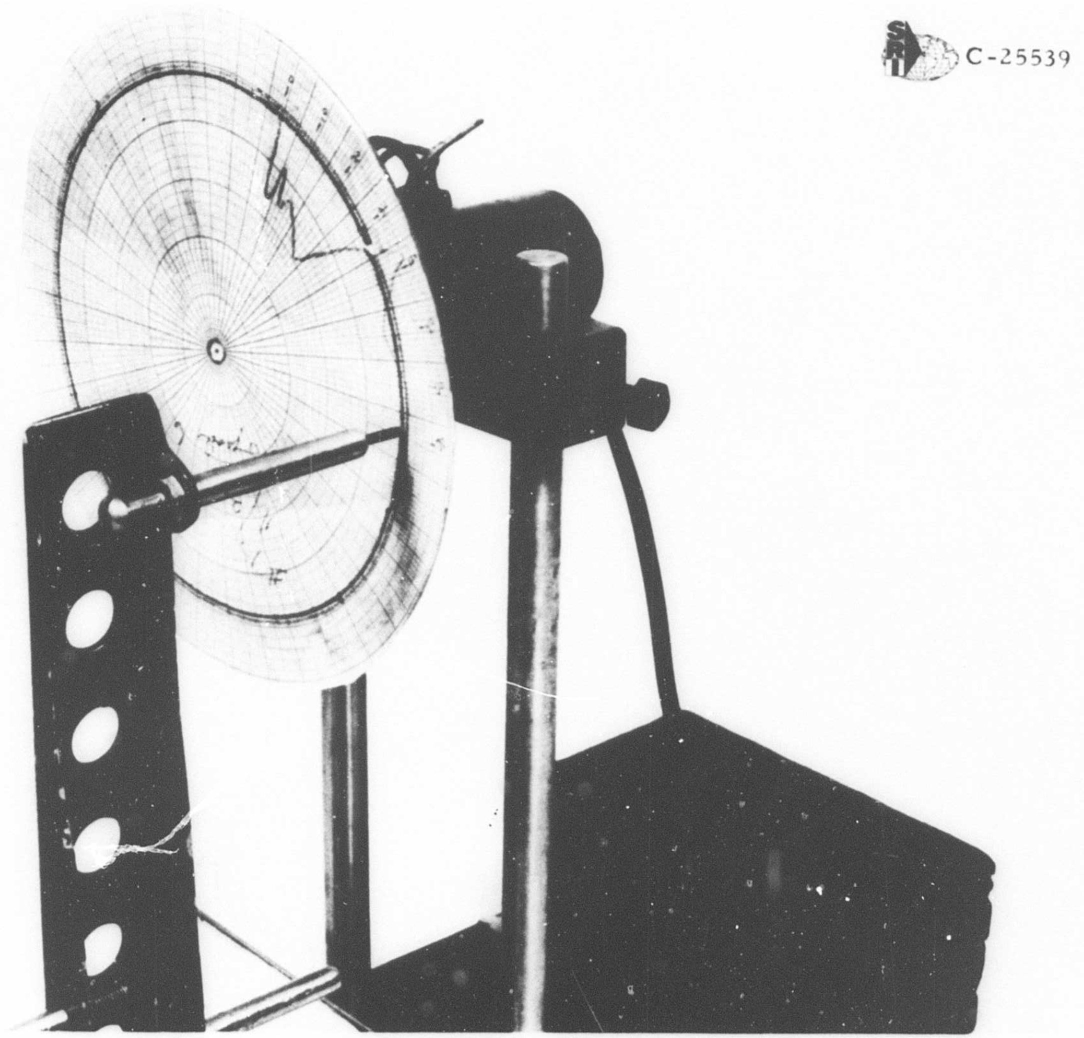


Figure 26. Mechanical Instrumentation System

7.83 inches above ground level and a similar history traced with a pen 3.58 inches above ground level. By subtracting these two displacement time histories and dividing by the distance between the pens, one obtains both the rotation and horizontal deflection at any location as functions of time. A separate pen 2.81 inches above ground level traces the vertical deflection as a function of the horizontal deflection on a stationary piece of paper. This procedure is well adapted to field work with excellent accuracy available. One degree of angular rotation represents approximately one millisecond of time on the rotated disks.

Results plotted in cylindrical coordinates when rectangular coordinates are better adapted to reporting the data represent the one disadvantage of this instrumentation scheme. To combat the difficulty, a system was developed for tracing the data as presented in cylindrical coordinates and automatically replotting the results electronically to any scale in rectangular coordinates. We achieve the transformation by using a slide wire as a voltage divider to measure displacement, a linearly variable resistance pot as a voltage divider to measure time (the angle of rotation), and a Mosley X-Y plotter to retrace the results. Typical traces of experimental results are presented throughout Section VII.

Additional Experimental Data

The author intends to include test results on foundation anchoring elements under short duration loads in Phase III of this program. These durations are to be very short compared to the natural period to obtain test results in the impulsive loading realm. Such experimental results have value for analyses of artillery without recoil mechanisms. The possible merits of a non-recoiling howitzer have already been presented in Section V.

To be included in the future experimental work will be results on interference effects. Interference effects arise when foundation elements are in close proximity to one another. These interference effects are utilized in providing additional anchorage when two spades in close proximity form a grouser. In essence, a grouser can be represented by a spade with an effective width greater than the combined widths of the spades comprising the grouser. A picture of a holder and two spades for the study of interference effects may be seen in Figure 27. The spacing between the spades can be systematically varied. Results from multielement tests will be compared to results from single anchoring element tests to discover the effective width of both spades and stakes in close proximity.

Summary

In summary, the overall objective of the data gathering program is to provide the weapon foundation designer with information which

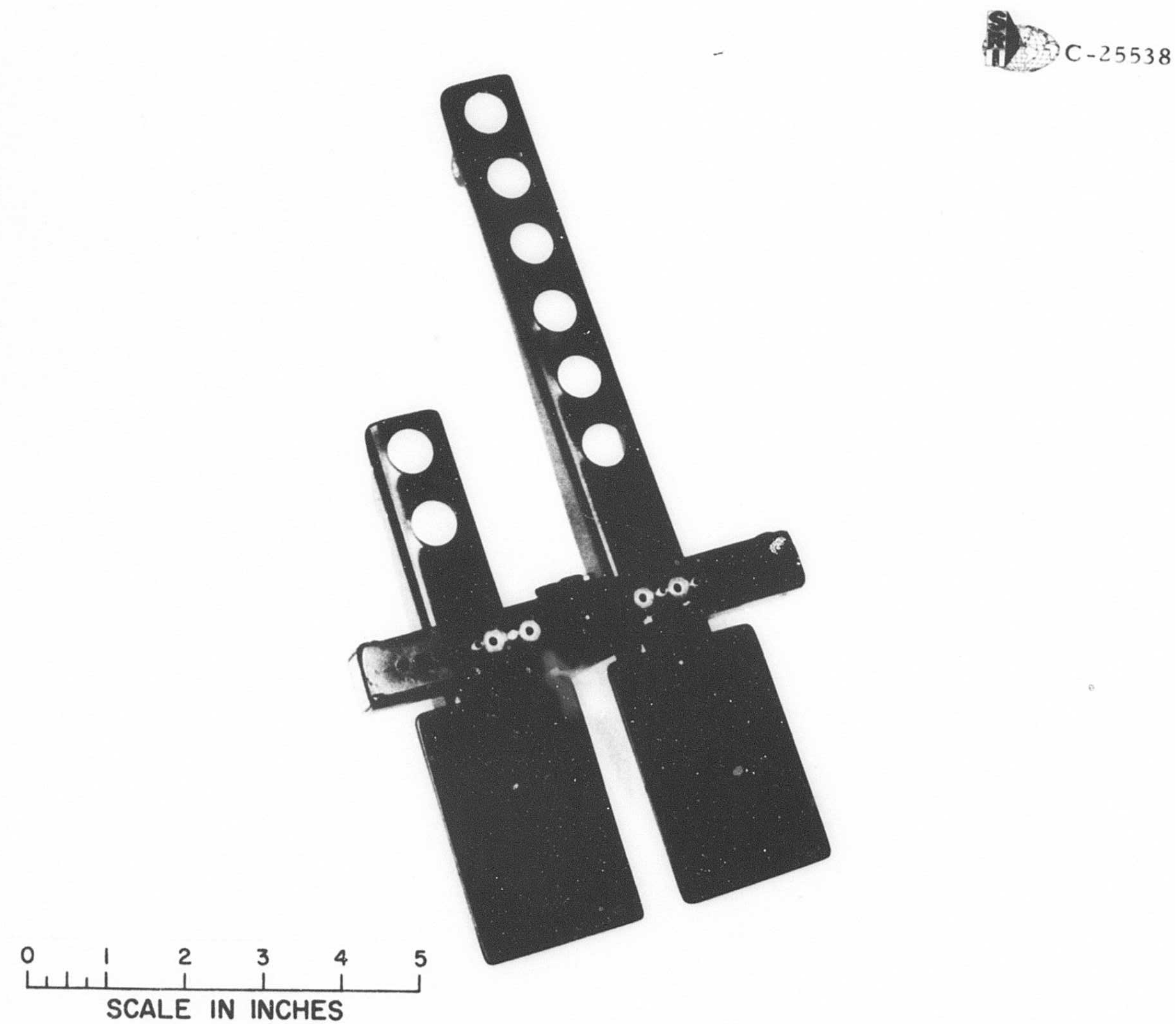


FIGURE 27. GRIPPING DEVICE AND SPADES FOR STUDYING INTERFERENCE EFFECTS

assists him in making reasonable predictions of displacements and rotations for various future artillery foundations. This program restricts itself to obtaining information on a limited number of typical weapon foundation elements subjected to a narrow range of loads considered typical of proposed future weapons. The program has been designed to obtain experimental data for an analysis to predict artillery foundation response. The final report for Phase III would present in a useful format the experimental data and would recommend procedures for interpreting and using the data in a dynamic analysis.

VII. EXPERIMENTAL RESULTS OF SPADES IN CLAY

Because of the limited time and funds in Phase II, the author decided to concentrate on obtaining experimental spade results at the clay test site. Many experimental results have been obtained using 1/4 scale elements; however, these results are not presented in this report, as they will be incorporated with many more results in the Phase III Final Report. The author did pursue the importance of piston mass on the experimental results and the significance of the vertical force on the horizontal translation and rotational response of the anchoring elements. In addition, a comparison was made between the horizontal displacements experienced by transiently loaded 1/3 and 1/5 scale spades. All experimental results were obtained using the gripping devices and plates mounted on these devices shown in Figure 28. The results obtained by varying the mass of the piston, the vertical force applied to the anchoring elements, or the size of the anchoring element and forces applied are the contents of this section.

Significance of Piston Mass

The 1/3 scale anchoring plate shown on the 1/3 scale gripping device of Figure 28 was used in determining the importance of the mass of the piston that applies the load to the anchoring elements. Our piston weighs approximately 2 lbs. Compared in Figure 29 are the deflection time histories for tests under identical conditions, except the piston

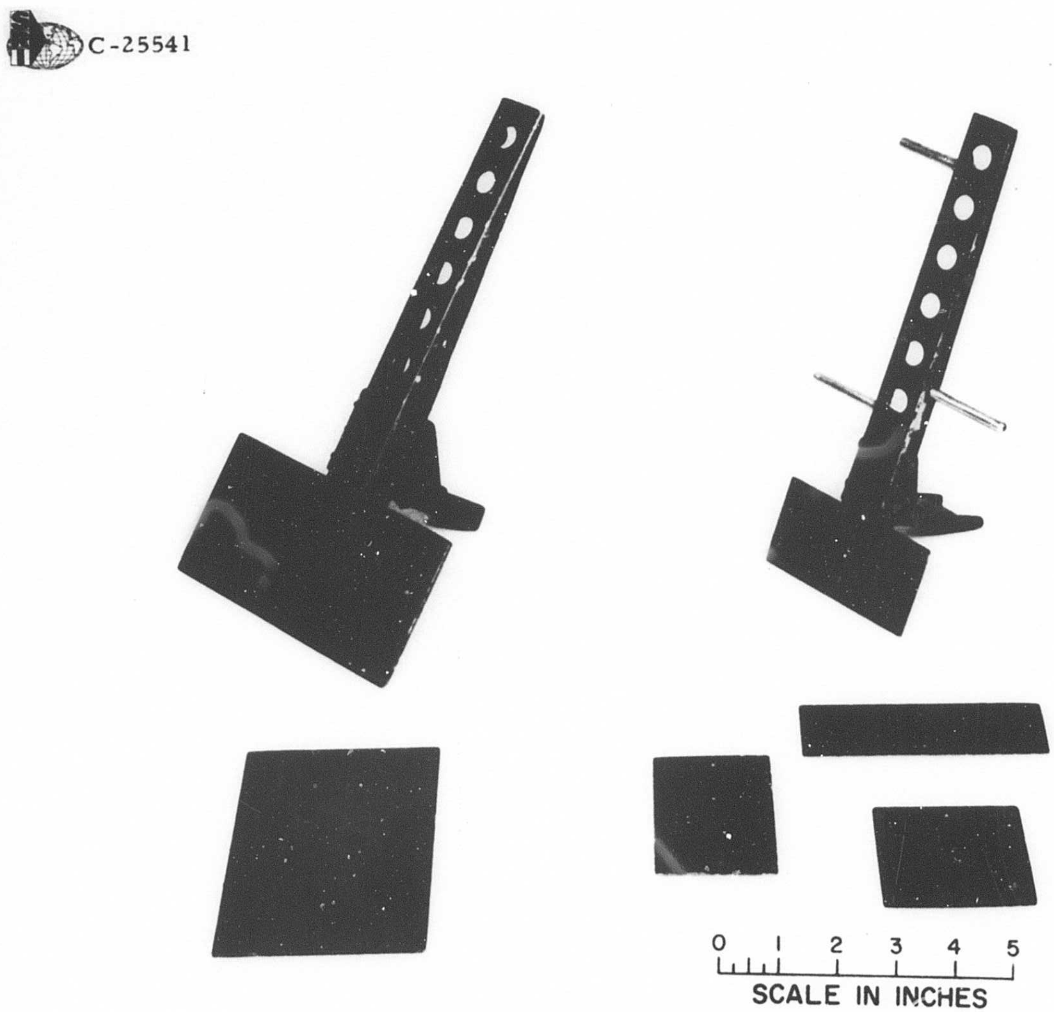


Figure 28. 1/3 And 1/5 Scale Spades And Gripping Device

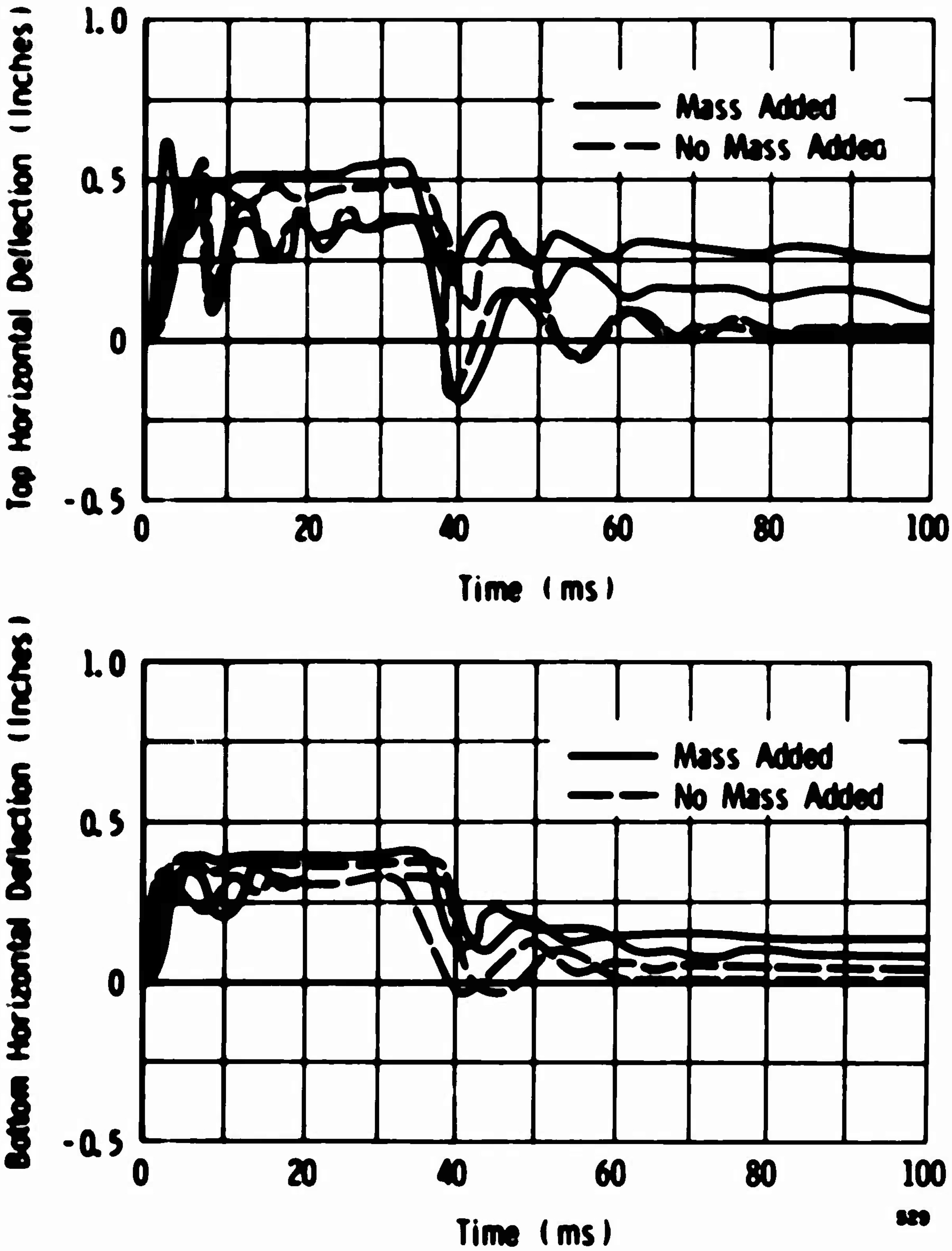
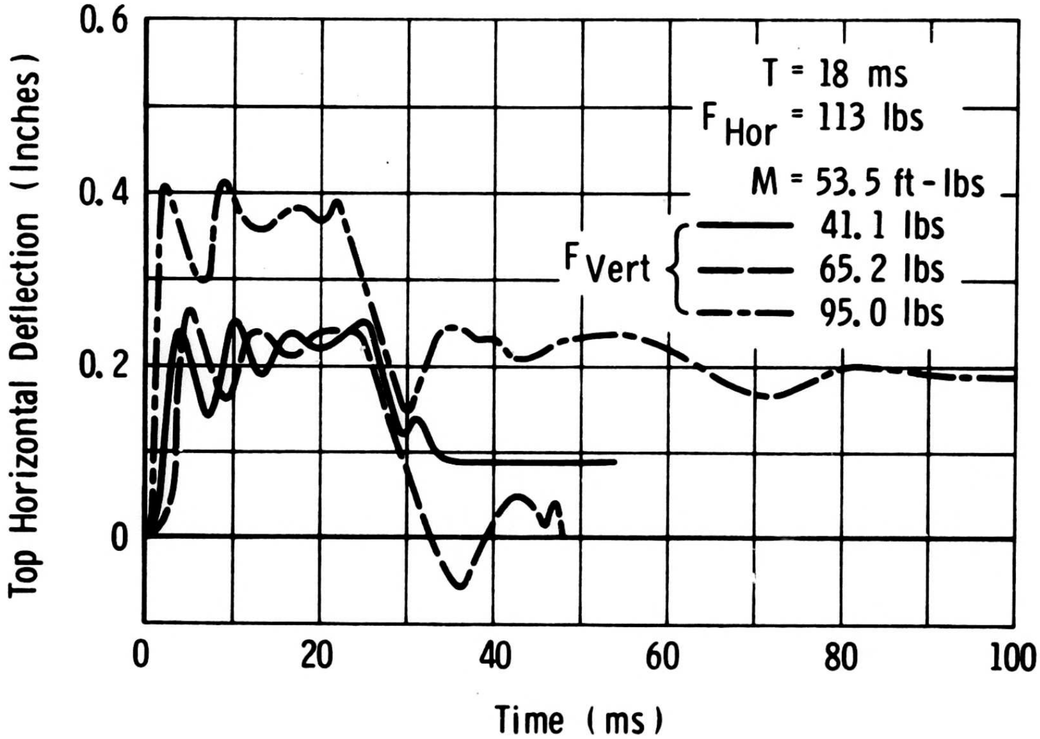


Figure 29. Tests To Determine The Significance Of Piston Mass

applying the load weighed either 2 lbs or 9-1/4 lbs. One readily observes that all results duplicate each other within the experimental accuracy; therefore, the mass of the piston is an insignificant parameter in our study.

Coupling of the Vertical Response

As mentioned in Section V on the dynamic response of howitzers, Barken[10] indicates that horizontal displacements and rotations are coupled, but the vertical displacement is generally uncoupled or can accurately be assumed to be uncoupled. One must note that Barkan only considers industrial vibrating or impacting foundations where little residual motion can be tolerated. Our weapon foundations exhibit significant residual motion with each impact, and experimental results in Figure 30 show that the vertical response is coupled with the horizontal displacements and rotations. To obtain the plots of deflection versus time in Figure 30, the author loaded the 1/5 scale anchoring element and holder shown in Figure 28 with a horizontal force of 113 lbs and a constraining moment of 53.5 ft-lbs, for a duration of 18 milliseconds. The vertical force on the anchoring element for different "set-ups" was systematically varied at 41.1 lbs, 65.2 lbs, and 95.0 lbs. The difference obtained in deflection time histories definitely substantiates that the vertical response of the anchoring elements is coupled with the horizontal and rotational response.



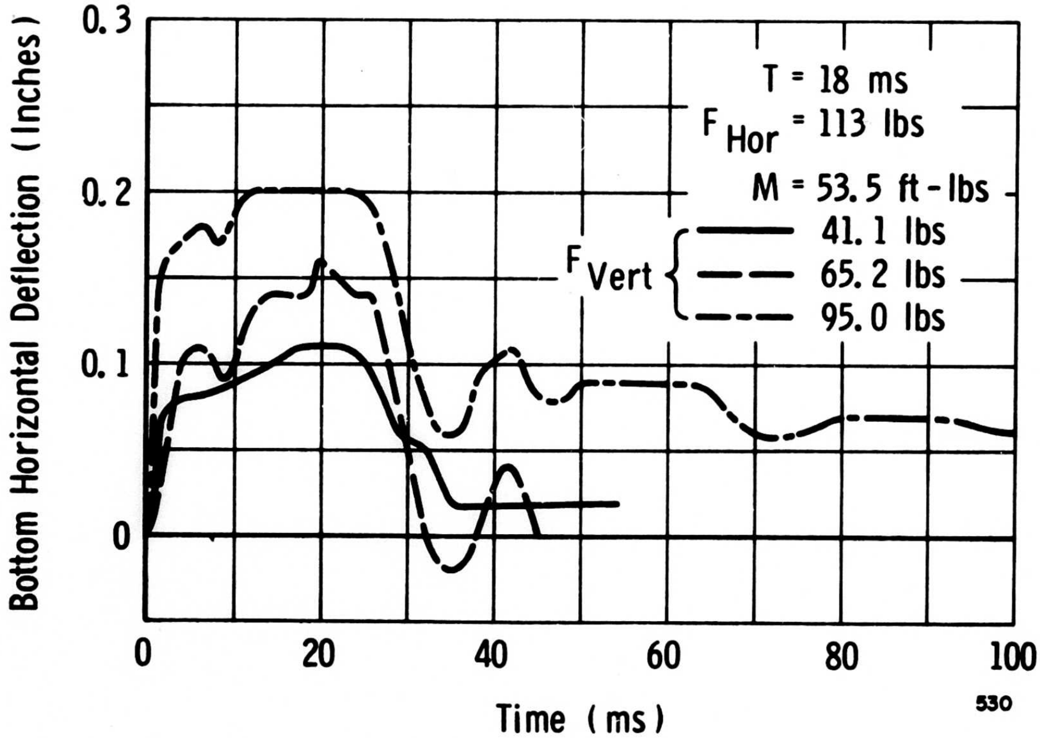


Figure 30. Tests Conducted Varying The Vertical Force

Comparison Between 1/3 and 1/5 Scale Spades

The author conducted a series of 1/5 scale tests in the clay soil using the 1/5 scale holding device and plate shown in Figure 28. The horizontal force applied to this 1/5 scale anchoring element was 113 lbs, the constraining moment was 53.5 ft-lbs, the vertical force was 95.0 lbs, and the duration was 18 milliseconds. The resulting 1/5 scale deflection time histories are presented in their corresponding 1/3 scale magnitudes as shown by dashed lines in Figure 31. A 1/3 scale series of tests was conducted to compare 1/3 scale anchoring elements to 1/5 scale elements in the clay soil. A corresponding 1/3 scale element had applied to it a horizontal force of 314 lbs, a constraining moment of 248 ft-lbs, a vertical force of 263 lbs, and a duration of 30 milliseconds. Such a scaling constitutes replica scaling, the procedure followed throughout this study. 1/3 scale results are shown in Figure 31 by a solid line. One observes that time scales excellently; however, the magnitude of the deflections scale poorly. No explanation exists to explain this discrepancy, particularly when excellent correlation existed between the prototype and model howitzers in this soil. One should note that a considerable resonance occurred early in the loading for the penholder gripping the 1/3 scale spade. Possibly this resonating structure drove the 1/3 scale spade, as the details in the 1/3 and 1/5 scale traces are similar after this resonance has dissipated. In Figure 32, the author shifted the 1/5 scale ordinate (the deflection) to make the 1/5 scale results overlay

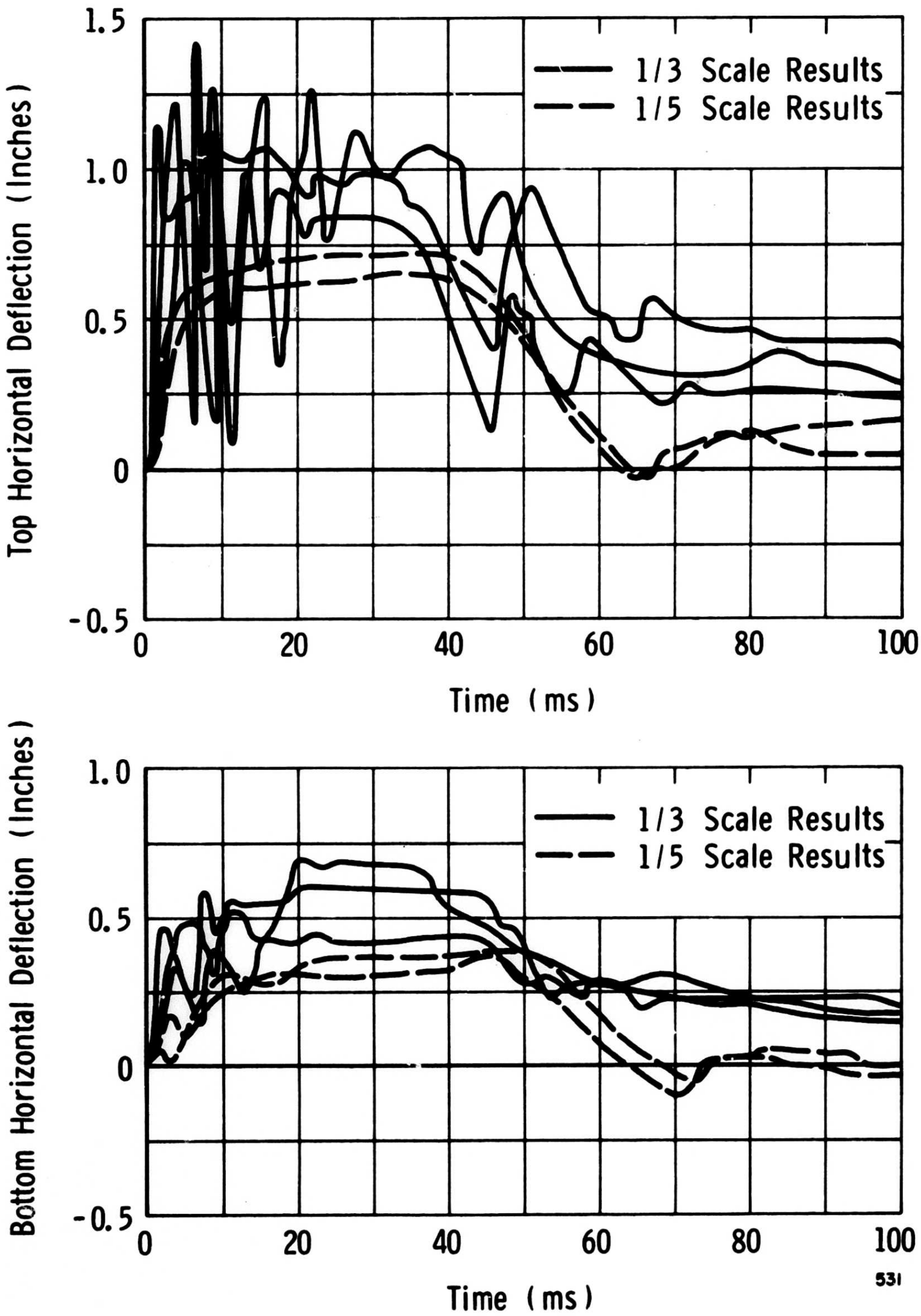


Figure 31. 1st Series Of Tests Comparing 1/3 And 1/5 Scale Spades

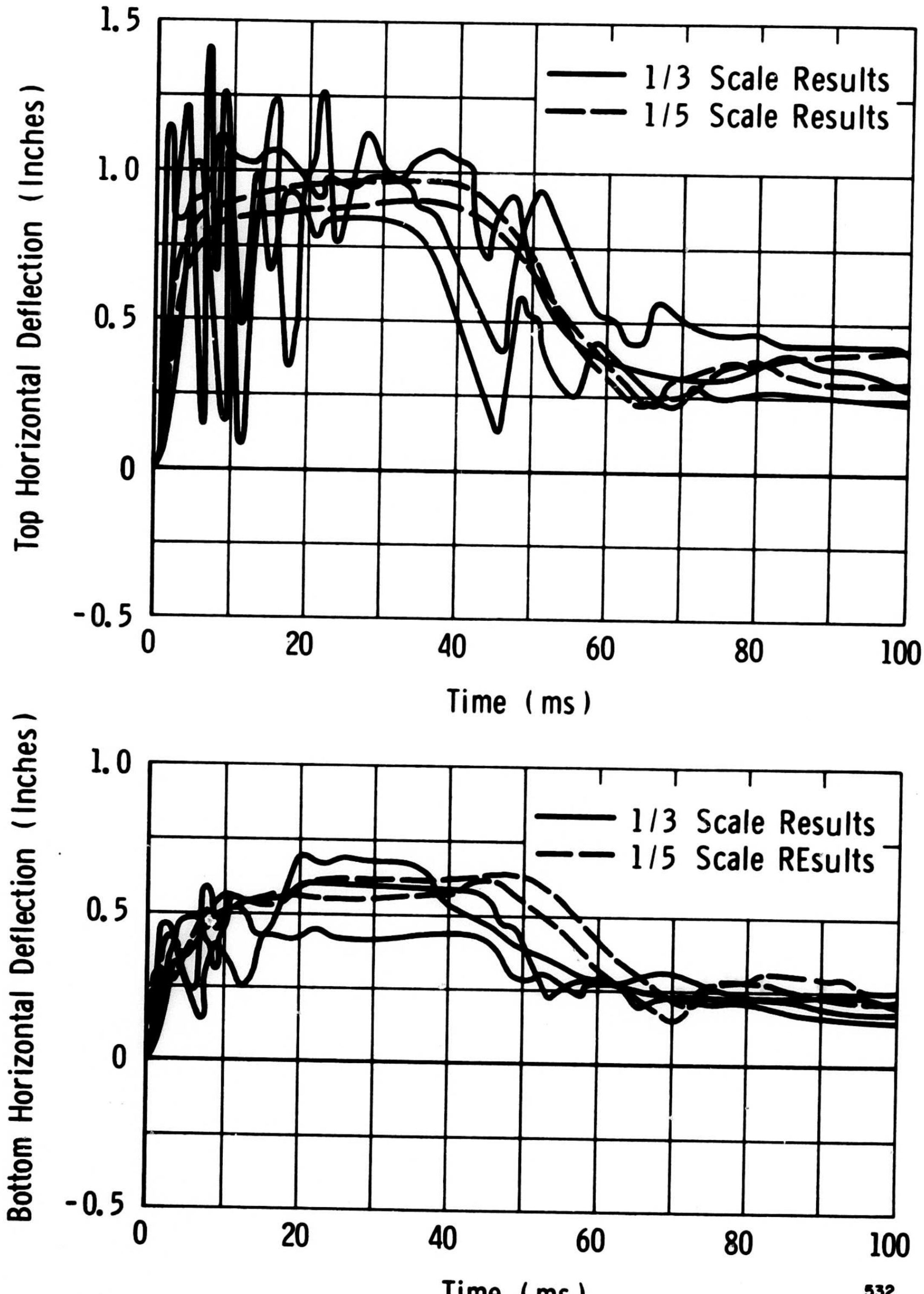


Figure 32. 1st Test Series With The Ordinate Shifted

1/3 scale results. Excellent correlation then exists between 1/5 scale and 1/3 scale results from this transformation of the origin. Therefore, the details in 1/3 and 1/5 scale traces agree excellently after the maximum deflection has been obtained (after resonance).

Assume one cannot scale the initial seatings of 1/5 scale and 1/3 scale elements, then the rebounding of the spades would scale excellently, but the initial displacement experienced by different size elements would <u>not</u> correlate. This explanation provides an additional reason for lack of agreement between 1/3 and 1/5 scale results in the initial deflections. To determine whether a resonating penholder drove the anchoring elements, or the inability to implant different size spades in a scaled manner accounts for the lack of agreement, the author conducted a second series of experiments.

A stiffer 1/3 scale penholder was manufactured to eliminate the resonances, and another identical series of tests was performed to see if a non-resonating holder caused the lack of agreement. The results from this series are shown in Figure 33. Excellent correlation resulted. Apparently the resonating structure drove the anchoring element.

One should note that this comparison between 1/3 and 1/5 scale anchoring elements has been conducted at the clay test site. We made no similar comparison at the sand test site. Complications may arise in a similar manner to those that arose at the sand test site in the howitzer model-prototype comparison. The details and explanations

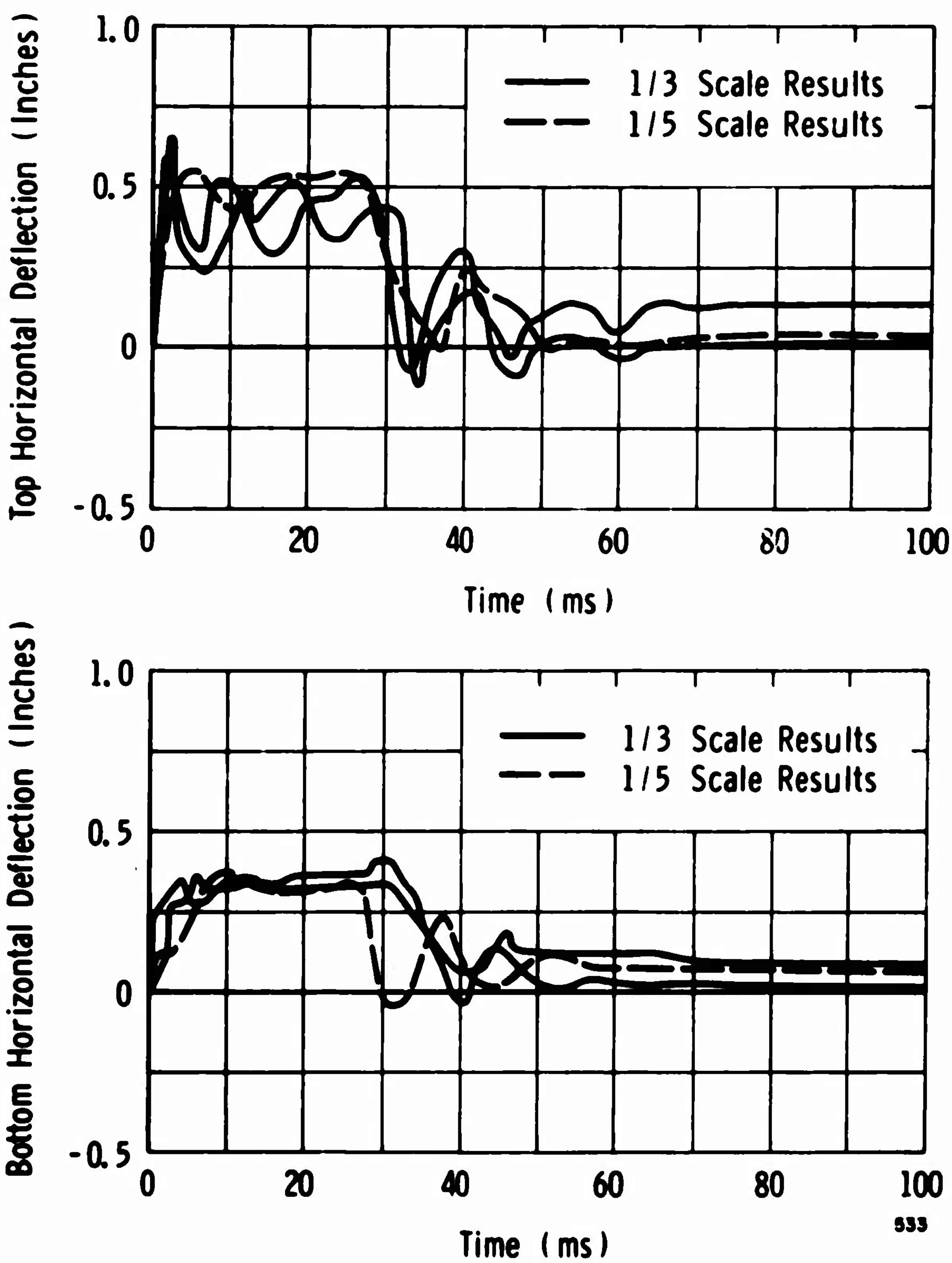


Figure 33. 2nd Test Series Comparing 1/3 And 1/5 Scale Spades

associated with such difficulties have already been presented in Sections III and IV.

Summary

Some of our experimental results for spades anchored in clay have been presented in this section. The sub-section on the significance of piston mass demonstrates that the mass of the piston loading the anchoring elements is an insignificant parameter in the problem provided the mass is small.

In tests demonstrating the importance of the vertical force in the horizontal displacement and rotations experienced by an anchoring element, we demonstrate that the vertical motion is coupled with the horizontal translational and rotational responses when significant residual displacements occur.

Finally, a limited 1/3 scale and 1/5 scale comparison has been made of spades anchored in clay soil. After modifying a resonating penholder, excellent correlation resulted.

VIII. DISCUSSION AND CONCLUSION

The author believes this Phase II program of a three phase research effort to assist the artillery foundation designer in developing more stable future weapons was very successful. Reasonable agreement exists in comparing most model and prototype results. Where the agreement is lacking, reasons exist to explain the lack of correlation. A model loading device has been constructed capable of applying square wave impulses with forces up to 1200 lbs for durations between 10 and 120 milliseconds. This model loading device was used to load a model of a 105 m.m. howitzer and currently loads model anchoring elements, the components of artillery foundations.

Comparisons have been presented of the residual rotations and displacements experienced by: (1) a 105 m.m., M2A2 howitzer with locked and unlocked wheels, (2) a 1/5 scale replica model in clay at different moisture contents, (3) a model and prototype howitzer in clay, and (4) a model and prototype howitzer in sand. The correlation in clay is good; whereas, the correlation in sand is poor. The lack of agreement in sand can probably be attributed to soil layering effects causing soil pore pressures to be prematurely dissipated and soil gravitational effects to be distorted.

Considerable insight was obtained into the dynamic response of a howitzer foundation. This response is coupled, may be either in-phase

or out-of-phase, and lies in either the dynamic analysis realm or the impulsive loading region. Experimental results from 1/5 scale replica model tests demonstrate that significant improvement can be forthcoming in the design of weapons that minimize foundation residual rotations provided a suitable dynamic analysis procedure is developed. In addition, we have observed that a recoiling howitzer can under certain conditions increase weapon stability while reducing weapon stability under other conditions. Under some conditions, a non-recoiling howitzer would experience exactly the same residual foundation motions as its recoiling counterpart. A coupled multidegree of freedom dynamic foundation analysis is required to properly optimize the design of weapon foundations.

A data gathering program has been designed and initiated for the collection of experimental data on the response of foundation anchoring elements to assist the gun designer in making reasonable predictions of displacements and rotations for various future artillery pieces. This program restricts itself to obtaining information on a limited number of typical weapon foundation anchoring elements subjected to a narrow range of loads considered typical of proposed future weapons. The final report for Phase III would present in a useful format the experimental data and would recommend procedures for interpreting and using the data in a dynamic analysis.

IX. REFERENCES

1. Nevill, Gale E., Jr., Modeling Studies of the Response of Weapon Foundations in Soils, Phase I, Final Report, June 1963, Contract No. DA-23-072-ORD-1375, Task Order No. 13.

2. Development of Weapon Foundation Design Data, SwRI Proposal 2-4399, prepared for Basic Research Branch, Research and Development Division, U. S. Army Weapons Command, Rock Island, Illinois, December 17, 1965.

3. Whitman, Robert, "The Behavior of Soils Under Transient Loadings," Proceedings of 4th International Conference on Soil Mechanics and Foundations, Vol. 1, (1957).

4. Holland, Cecil, Jr., "Investigation of the Effect of Rate of Loading on the Unconfined Compressive Strength of Compacted Soils," Master's Thesis, University of Washington, (1960).

5. Richardson, Archie, Jr., "Effects of Rate of Strain on Stress-Strain Behavior of Saturated Soils," AD 272 653, April 1961.

6. Schimming, B. B. and Saxe, H. C., "Inertial Effects and Soil Strength Criteria," Proceedings of the Symposium on Soil Structure Interaction, University of Arizona, (1964).

7. Converse, F. J., "Foundations Subjected to Dynamic Forces," Chapter 8 in book edited by G. A. Leonards, Foundation Engineering, McGraw-Hill, N. Y., (1964).

8. Halajian, J. D., "Soil Behavior in a Low and Ultrahigh Vacuum," ASME, 64-WA/AV-14, (1964).

9. Roddy, D. J., Rittenhouse, J. B., and Scott, R. F., "Dynamic Penetration Studies in Crushed Rock Under Atmospheric and Vacuum Conditions," J. P. L. Report No. 32-242, (1962).

10. Barkan, D. D., Dynamics of Bases and Foundations, McGraw-Hill, New York, (1962).

APPENDIX

SOIL TEST SITE SELECTION

Introduction

Due to the necessarily limited scope of this program, appreciable thought was devoted to the selection of soil sites for testing. Several different criteria were considered including geographical distribution, probable severity of foundation problems, probable mode of foundation behavior, soil mechanical properties, classification by particle size, moisture content, minerology and history. We concluded that a classification by grain size was most appropriate because:

1) the vast spectrum of soil types can be divided into two groups:
   a) Granular Soils
   b) Cohesive Soils
2) the boundary between these groups is best represented by grain size.

Before discussing each group separately, a few comments about general site characteristics are in order.

Any test site had to be near San Antonio and easily accessible by truck. The site's minimum bearing capacity should support a man or jeep, and the maximum bearing capacity could be established by the ability to emplace a foundation. This upper limit depends on the type

of foundation; however, our vague measure bounds the problem sufficiently, and these limits appear appropriate, as similar ones currently exist for all artillery sites.

Only soils above the ground water table were considered, as our study is concerned with surface soils. Thus, saturation by capillary action only and not by penetration has been considered. To simplify the study further and to avoid complicated interactions, soil test sites had to be relatively free of rocks and boulders. Furthermore, the site required a soil with uniform strength parameters and properties over an area of around 1500 square feet in order that we might run many tests under identical initial conditions. Ideally, the site should possess the same soil to an infinite depth; however, a layer of the same soil five or more feet deep could suffice. At our clay site, several inches of surface soil had to be excavated to reach an under-lying layer. These numerous general site characteristics placed demands on us, but they have been met in the San Antonio vicinity.

Granular Soil

Large-grained soils with particle diameters greater than about two microns possess insignificant interparticle forces and are termed cohesionless, granular, and/or sandy soils. In these soils, gravitational forces determine the engineering characteristics. Since nature possesses few coarse-grained granular soils of the gravel nature, this

study concentrated on poorly graded, medium to fine-grained soils. For such soils, the relative density is the predominant strength parameter.

The author selected a sand test site at Mr. Edwin Espey's A-1 Sand Quarry off U.S. Highway 281 in southern Bexar County. The soil consisted of a white silica sand that is geologically classified as coming from the Claiborne Group in the Eocene Series of the Cenozoic Era. A grain size distribution for this soil may be seen in Figure 34.

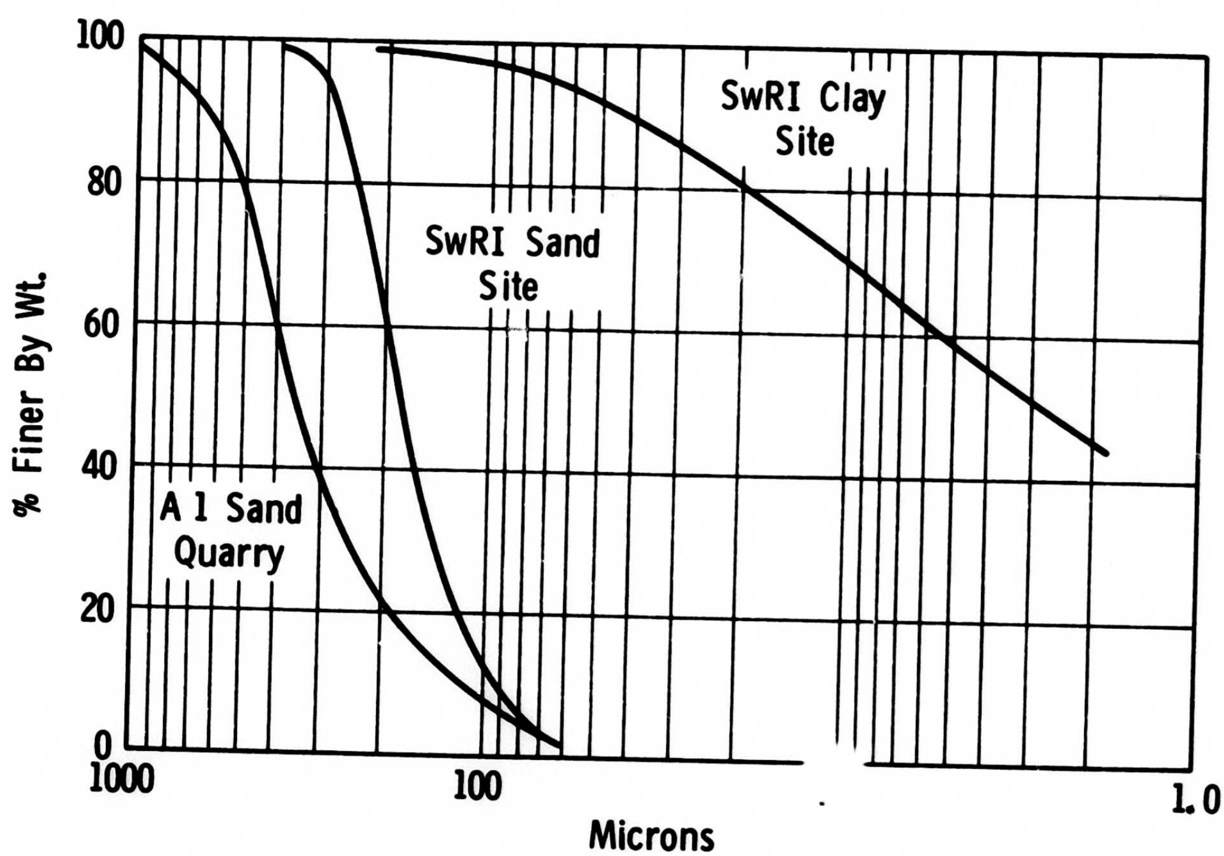


Figure 34

GRAIN SIZE DISTRIBUTION OF TEST SOILS

According to the M. I. T. classification system, this sand would be termed medium-grained, poorly graded. It possesses a minimum dry density of 92 $^{lb}/_{ft^3}$ and a maximum dry density of 105.4 $^{lb}/_{ft^3}$. The inplace dry density is 103.2 $^{lb}/_{ft^3}$, giving an inplace relative density of 87%. No permeability tests were conducted on this sand; however, Hazen's Equation yields an approximate coefficient of permeability of 1.4×10^{-2} $^{cm}/_{sec}$. This very permeable soil possesses no cohesion, but has an internal friction angle of 29.8 degrees when tested dry in a shear box.

All Phase II granular soil tests were performed in this sand with the single exception of the tests investigating the influence of load duration in wet sand, Figure 19 in Section V. These few experiments were performed at a sand test site on SwRI's grounds. In a previous program, a sand test bed was constructed from a special sieving of sand obtained at the A-1 Quarry. Naturally the Institute sand possesses similar geological properties to the sand at the A-1 Quarry. Because the Institute sand comes from a special sieving, the grain size is smaller than the inplace A-1 sand (see Figure 34), and classified as fine-grained, poorly graded. The Institute sand has a low relative density of 62.4%. This Institute sand site will be used for all data gathering on anchoring elements in sand during Phase III, for the site is more conveniently located. We did not use the Institute site during prototype howitzer firings, as it is relatively small.

Cohesive Soil

Cohesive soils or clays are considered as having adhesive tendencies among grains. If dried out, a cohesive hard mass of material remains which can be pulverized to a powder. These fine-grained or cohesive soils exhibit a more complex behavior than the granular soils, as the major forces involved are adhesive or cohesive interparticle ones. Such factors as void ratio, water content, degree of saturation, type of structure, compressibility, thixotropy, sensitivity, activity, prior loading history, ion concentration in the electrolyte, valence of the ions in the electrolyte, and temperature all influence the soil's properties. Inasmuch as surface clays which tend to be over-consolidated are considered, the effects of sensitivity and thixotropy will be minimal. Further, since swelling is not important, clay activity was neglected. The influences of ion concentration, soil structure, temperature, and valence of the ions in the electrolyte were not included in this study, as their behavior is reflected in the measured engineering properties of the soil. Because moisture content and degree of saturation will be very important variables, the clay site should and will be visited at various seasons in Phase III to test the same soil under different moisture contents.

Nature seldom presents pure deposits of clay; therefore, we chose a test site with a sufficiently large fraction, about 45%, of particles smaller than two microns. Our clay test site is a field, on the

Institute grounds, of an organic, highly compressible, black, silty clay, locally termed Houston Black. The grain size distribution of Houston Black may be seen in Figure 34. This soil has a liquid limit of 74.9% and a plastic limit of 36.5%. Thus its plasticity index is 38.4% and activity index 85%. According to the Arthur Casagrande Classification System, this clay lies below the A-line in the region of highly compressible, organic clays. Houston Black geologically originates from the Gulf Series in the Cretaceous System of the Mesozoic Era. The soil's coefficient of permeability, as determined from a constant head permeability test in a triaxial machine, is 1.0×10^{-8} $^{cm}/_{sec}$. Three unconsolidated-undrained rapid triaxial tests were run on the clay without measuring pore pressures. On the Coulomb-Mohr total stress failure envelope, the fully saturated Houston Black has an apparent friction angle of 7.9 degrees and an apparent cohesion of 120 $^{lb}/_{ft^2}$. All of our tests on cohesive soil have been conducted in this medium.

Concluding Comments

Of obvious omission from this study are the peats or organic, root and vine infested soils which exist in many grass lands and jungles. Perhaps at a later time, peat and wind-blown granular soils known as loess might be added to this study.

We feel that the site selection as presented here promises a comprehensive program designed to cover a wide range of soils and conditions. Quite naturally, experimental results in Phase III may and should alter any plans.

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13. ABSTRACT

In this report, the author first describes the design of a portable model foundation loading device capable of applying square wave impulses with forces up to 1200 lbs for durations between 10 and 120 milliseconds. The model loading device is used to simulate the load on the non-recoiling parts of a howitzer foundation in both sands and clays. An important part of this program is the comparison between residual displacements and rotations resulting from loading a geometrically similar 1/5 scale, replica model and firing a 105 m.m., M2A2 howitzer. Through this program, considerable insight has been obtained into the dynamic response of artillery foundations. The foundation response lies in neither a quasi-static analysis nor an impulse analysis realm. Load level, the duration of loading, soil strength, the mass of the foundation, and the mass moment of inertia of the foundation are all significant in determining the response of artillery foundations. Furthermore, the vertical translational, horizontal translational, and rotational responses of the foundation should be coupled in any dynamic analysis of the response. This report includes plans for an experimental program to develop data for analyzing the response of artillery foundations and closes with a discussion of some experimental results in clay soil.

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